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ACTIVE MEASURES FOR REDUCING THE GLOBAL CLIMATIC IMPACTS OF ESCALATING CO_2 CONCENTRATIONS†

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Abstract—The buildup of CO_2 by fossil-fuel burning and associated climatic changes have become the subject of intensive investigations. Although the time scale on which significant climatic changes (e.g. mean temperature changes of several degrees, appreciable changes in global and regional rainfalls and winds, etc.) are expected to occur is long, it has been noted that the magnitude of the energy system is so vast that modifications in the primary resource mix should preferably be initiated within a decade or sooner. The notion that the most economical energy source will be replaced globally in response to longterm climate model predictions is probably false. Before policy matters of this type can be discussed reasonably, careful assessments must be made of alternative global measures that do not require curtailments of fossil-fuel applications. This study on active measures for reducing climate changes caused by escalating CO_2 concentrations deals with potentially important areas of research. We find: (a) reductions in the solar input to the Earth by reflecting sunlight directly are prohibitively costly; (b) desired changes in Earth albedo through judicious introduction of small particles can probably be accomplished at acceptable cost through the use of modified combustors on high-flying aircraft.

1. INTRODUCTION

Continued combustion of fossil fuels is expected to lead to a doubling of the atmospheric CO_2 concentration during the period 2035–2050[1–3]. This increase in atmospheric CO_2 concentration is expected to cause mean global temperature rises of 3–4°C[1–3]. Global climate changes associated with mean global temperature rises of this magnitude are likely to be of unprecedented extent in human history, not easily reversible, and perhaps disastrous to existing social structures[4].

We examine the consequences of implementing either of two active counter-measures in order to reduce the solar energy input to the Earth. As a rough estimate of allowable annual costs for a major enterprise of this type, we use 10% of the current (1983) world-wide value of the fossil-fuel systems, i.e. 10% of $\$2 \times 10^{12}$ or $\$200 \times 10^9$. We will show that this level of expenditure is far too small for implementation of a reflecting, space-based mirror system to reduce the solar energy input by 1%. It is, however, much larger than our cost estimate for increasing the effective Earth albedo by 1% through the judicious distribution of small particles. It is apparent that any of the measures needed to reduce the solar energy input must satisfy the following two constraints: (1) program implementation can be interrupted at any time if it becomes clear that the predicted changes do not occur; (2) following project completion, the magnitude of the achievable effects can either be augmented or reduced by measures that are cost-competitive with the initial program costs.

2. NON-TRACKING, SPACE-BASED MIRROR SYSTEMS TO REFLECT 1% OF THE INCOMING SOLAR RADIATION

It has been estimated that a 1% decrease in the solar energy input will cause a 1.5°C decrease in the mean global temperature[5]. This change may be effected by the placement of mirrors as satellites in synchronous orbits in such a manner as to reflect 1% of the incoming solar energy back into space. At first sight, synchronous orbits appear to be preferred because of the expense and difficulty of designing propelled systems that track the sun. Our analysis should yield low order of magnitude estimates for such an undertaking.

Twice‖†† the cross sectional area of the Earth is $2A_e = 2\pi r_e^2 = 2.548 \times 10^8$ km^2 since the mean Earth radius is $r_e = 6.368 \times 10^3$ km. If the atmosphere were

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‖The factor of two arises because the sun illuminates the Earth from one side only so that one half of the reflector area is inactive at any given time.

††Nomenclature is given in Appendix at end of paper.

not present, we could simply reflect solar radiation that is incident on 1% of this area. The use of non-tracking, space-based mirrors in any orbit will require area blockage larger than $10^{-2} \times (2A_e)$. We may therefore regard the construction of reflectors for $10^{-2} \times (2A_e)$ as a very optimistic lower bound of the cost for any non-tracking, space-based mirror system. Since the construction cost for mirrors blocking $10^{-2} \times (2A_e)$ is excessively large, we conclude that any non-tracking, space-based mirror system will be prohibitively costly.

We consider thin-walled, spherical satellites which may be stored in compact form and then inflated when positioned in space. Each satellite has a radius of 300 m with a cross sectional area of 2.827×10^{-1} km^2. The total required blockage area of 2.548×10^6 km^2 is obtained by using 9.011×10^6 satellites of 300-m radius. We assume that the satellites are constructed of reflectorized mylar with a thickness of 2 mils and a density of 0.05 lb/in^3, which is about one half that of aluminum. Hence, we require 1.217×10^7 ft^2 of mylar per satellite with a weight of approx. 175,000 lb. It has been estimated that by the year 2000 we may be able to place material in space at a cost of \$200/lb. Neglecting the cost of manufacturing of the mirror satellites, we obtain a launching cost of $\$315 \times 10^{12}$.

The calculated program cost is far in excess of allowable costs for the specified mission objectives. For this reason, we conclude that direct control of solar energy input by the use of reflecting mirrors is not a viable programme.

3. TRACKING, SPACE-BASED MIRROR SYSTEMS

We have not analyzed in detail the complex problem of tracking, space-based mirror systems. It is, however, very unlikely that launching and tracking costs will be appreciably less than \$200/lb in orbits below synchronous altitudes. The principal change will be that the needed area blockage will approach the lower bound of $10^{-2} \times (A_e)$. We therefore conclude that a mission cost estimate of $(\frac{1}{2}) \times (\$315 \times 10^{12})$ cannot be reduced sufficiently to make tracking, space-based mirror systems for the purpose of reducing the solar energy input to the earth an economically viable approach.

4. EARTH-ALBEDO MODIFICATIONS BY USING SMALL PARTICLES†

4.1 *Monidisperse* 0.5 μm *particles between* 40,000 *and* 100,000 ft *above the surface of the Earth*

The incident solar radiant intensity I_0 is reduced to $(1-\beta)\, I_0$ by monodisperse particles that scatter light with unit efficiency factor (neglecting multiple scattering) when:

$$1-\beta = \exp[-k(r_2-r_1)] = \exp[-n\pi r_p^2(r_2-r_1)], \quad (1)$$

where n = particle number density, r_p = particle radius, and $r_2 - r_1$ = difference in the radial distances from the center of the earth at the radius where the particles are first (r_2) and last (r_1) encountered by the incident solar radiation. The total number of monodisperse particles needed under the specified ideal conditions is:

$$N_p = \frac{4}{3}\pi(r_2^3 - r_1^3)n = -\frac{2}{3}\frac{\ln(1-\beta)}{r_p^2} \times [(r_2^2 + r_1^2) + (r_1 + r_2)^2]. \quad (2)$$

The corresponding total particulate mass is:

$$m_p = \frac{4}{3}\pi r_p^3 \rho_p N_p = -\frac{8}{9}\pi\rho_p r_p[\ln(1-\beta)] \times [(r_2^2 + r_1^2) + (r_1 + r_2)^2]. \quad (3)$$

We consider monodisperse 0.5 μm particles, which are uniformly distributed between $r_1 = r_e + 40{,}000$ and $r_2 = r_e + 100{,}000$ ft. These altitudes were chosen in order to reduce particulate removal by precipitation. For $\beta = 10^{-2}$ and $\rho_p = 2\, g/\text{cm}^3$, we find that $n = 0.7$ particle/cm^3, which corresponds to $N_p = 6.56 \times 10^{24}$ particles and $m_p = 6.87 \times 10^{12}$ g = 15.2×10^9 lb.

4.2 *Climatic effects produced by particle-size distributions using a global circulation model* (*GCM*)

Reck[6] has considered what changes in extinction coefficient in the atmosphere would be necessary to counteract a doubling of the CO_2 concentration at 35° N latitude. She found that the extinction coefficient would have to be increased from its present value of 0.1 to 0.3 km^{-1} for an r^{-6} particle-size distribution [i.e. $n(r)/n(r_0) = (r_0/r)^6$] with $r_0 = 0.05\,\mu$m, a maximum particle radius of 10 μm, and allowing only for single scattering. The particles were distributed between 620 and 2500 ft altitude.

To counteract a doubling of the CO_2 concentration, we need to increase the extinction coefficient from its present value by 0.2 km^{-1}. For a continuous particle-size distribution, the linear absorption coefficient is:

$$k = \frac{1}{(r_{p,\max} - r_{p,\min})}\int_{r_{p,\min}}^{r_{p,\max}} [n(r_p)]\pi r_p^2\, dr_p$$

or, for $[n(r_p)] = [n(r_{p,\min})](r_{p,\min}/r_p)^6$,

$$k = \frac{\pi[n(r_{p,\min})]r_{p,\min}^3}{3(r_{p,\max} - r_{p,\min})}\left[1 - \left(\frac{r_{p,\min}}{r_{p,\max}}\right)^3\right]. \quad (4)$$

†In this highly simplified analysis, we assume that all particles scatter radiation without absorption. Light-absorbing particles will cause heating.

Thus,

$$n(r_{p,\min}) = \frac{3k}{\pi}\frac{r_{p,\max} - r_{p,\min})}{r_{p,\min}^3}\left[1 - \left(\frac{r_{p,\min}}{r_{p,\max}}\right)^3\right]^{-1} \quad (5)$$

and, for $k = 0.2\ \text{km}^{-1}$, $r_{p,\min} = 0.05\ \mu\text{m}$, $n(r_{p,\min}) = 1.52 \times 10^7$ particle/cm^3 since $r_{p,\max} = 10\ \mu\text{m}$. The number density for any particle radius r_p is:

$$n(r_p) = n(r_{p,\min})\left(\frac{r_{p,\min}}{r_p}\right)^6 = \left(\frac{3k}{\pi}\right)\left(\frac{r_{p,\min}^3}{r_p^6}\right) \times (r_{p,\max} - r_{p,\min})\left[1 - \left(\frac{r_{p,\min}}{r_{p,\max}}\right)^3\right]^{-1}. \quad (6)$$

We may now calculate the total mass of particles required for Reck's analysis from:

$$m_p = \frac{1}{(r_{p,\max} - r_{p,\min})}\int_{r_{p,\min}}^{r_{p,\max}} \frac{4}{3}\pi r_p{}^3 \rho_p \times [n(r_p)]\, V\, \mathrm{d}r_p', \quad (7)$$

where ρ_p is again the particle density and V is the total volume through which the particles are dispersed; in Reck's analysis, $V = (4\pi/3)(r_2{}^3 - r_1{}^3) = 2.920 \times 10^{23}$ cm^3 for $r_1 = r_e + 620$ ft and $r_2 = r_e + 2500$ ft. Using eqn (6) in eqn (7), we find

$$m_p = 2\rho_p V k r_{p,\min} r_{p,\max}\left(\frac{r_{p,\max}^2 - r_{p,\min}^2}{r_{p,\max}^3 - r_{p\min}^3}\right). \quad (8)$$

For $\rho_p = 2$ g/cm^3, $m_p = 1.168 \times 10^{13}$ g $= 25.8 \times 10^9$ lb.

This estimate is remarkably consistent with that obtained in Section 4.1. Thus, we find here that about 26×10^9 lb of particulate matter are needed to compensate for CO_2 doubling at 35°N, i.e. about 13×10^9 lb are needed for a temperature reduction of about 1.5°C. In Section 4.1, we found that about 15×10^9 lb are needed to reduce the Earth albedo by 1%, which also corresponds to a mean temperature reduction of about 1.5°C[5].

5. PARTICULATE LOADING OF THE STRATOSPHERE BY COMBUSTION PRODUCTS FROM SURFACE VEHICLES

It is easy to show that operations of surface vehicles are unlikely to lead to the specified particulate loadings of the stratosphere during a reasonable period of time. The current limit on particulate emissions for cars in California without catalytic converters is 0.54 g/mile; for cars with catalytic converters, it is 0.25 g/mile. Of the cars on the road in 1982, 81% had catalytic converters. We determine a high upper bound on particulate emissions from surface vehicles by assuming that all of the motor fuel is consumed by cars without catalytic converters. We also assume that these cars average 20 miles/gallon of fuel, which implies a loading of 2.38×10^{-2} lb of particulates per gallon of motor fuel consumed.

According to a 1981 report, 6.59×10^6 barrels of motor fuel per day were consumed in the U.S.[7]. Thus, the total U.S. consumption of motor fuel is 1.01×10^{11} gallons/yr. For particulate emission rates of 2.38×10^{-2} lb of particulates/gallon, this consumption will result in a total particulate loading of 2.4×10^9 lb/yr. If the world-wide consumption of motor fuels is three times that of the U.S., we obtain an estimated upper bound for the world-wide particulate loading by surface vehicles of 7.2×10^9 lb of particles/year. It is unlikely that anywhere near as much as 3% of this material will be convected upward into the stratosphere. In the unlikely event that 3% of the particulate emissions from surface vehicles reach the stratosphere and remain at high altitudes indefinitely, it would require more than 120 yr to distribute a particulate mass of approx. 30×10^9 lb. We therefore conclude that it is highly unlikely that motor vehicles will contribute significantly to high-altitude particulate loadings that are of sufficient magnitude to moderate the climatic impact of escalating CO_2 concentrations.

6. IMPLEMENTATION OF PARTICULATE DISTRIBUTIONS AT HIGH ALTITUDES

We shall now show that currently operating commercial aircraft may be used to distribute the desired amounts of particles in the course of their normal operations over about a 10-yr period. The only required operational change is redesign of the engine-combustion system to operate under richer than normal conditions and transform about 1% of the jet-fuel input mass to particulates.† There is little doubt that this objective can be implemented with negligible losses in engine performance. The proposed implementation program will involve jet aircraft with an aggregate capital cost of about $\$50 \times 10^9$ and using per year fuel valued at about $\$50 \times 10^9$ at an oil cost of about $30/bbl. Thus, the 10-yr implementation schedule represents the incidental use of fuel valued at about $\$500 \times 10^9$.

The preceding estimates are easily justified by noting that recent (1981) U.S. jet-fuel consumption was about 1.01×10^6 bbl/day[7]. If we assume that U.S. jet-fuel consumption represents approx. 33% of the worldwide use, then we find that the total worldwide consumption of jet fuel (in 1981) was about 3×10^6 bbl/day. Assuming that jet fuel has the density of kerosine (1.56 slug/ft^3 or ~ 0.804 g/cm^3), a 42-gallon barrel of jet fuel weighs 282 lb. Thus, on a worldwide basis, we burn about 8.46×10^8 lb/day of jet fuel. For operations over 365 days per year, the total fuel use is 3.09×10^{11} lb/yr.

We have found (see Section 4) that we need

†Alternatively, 1% of inert particulate matter may be added to the jet fuel for distribution during normal flights. The corresponding program cost would then be roughly the cost of the added inert material or, at $1/lb, about $\$15 \times 10^9$. In this highly simplified analysis, we assume that all particles scatter radiation without absorption. Light-absorbing particles will cause heating.

approximately 30×10^9 lbs of particles distributed between 40,000 and 100,000 ft in order to offset temperature rises associated with a doubling of atmospheric CO_2 concentration at 35°N latitude. This value represents 10% of the total yearly consumption of jet fuel on a world-wide basis. Since jet aircraft spend most of the flying time above 30,000 ft, it is appropriate to consider particulate production as a byproduct of jet-fuel combustion. We note that the annual particulate production will be 3×10^9 lb if 1% of the mass of fuel burned is exhausted as particles. Assuming that this particulate loading occurs above 30,000 ft and continues for approx. 10 yr, we find that the needed weight of particle injection has occurred. The critical questions of particulate distribution and atmospheric residence time remain to be examined.

The present EPA standard for stationary power sources is 0.03 lb of particulates per 10^6 Btu. This value implies that, if the aircraft industry were required to meet the EPA standards for stationary burners, civil aviation would contribute 1.85×10^8 lb/yr on a worldwide basis. At this rate, it would take over 160 yr to distribute the required mass of particulates. In order to distribute the required particulate mass in 10 yr, we would require that particulate emissions for jet aircraft be approx. 0.49 lb of particulates per 10^6 Btu.

7. CONCLUSION

The primary conclusion which we draw from this analysis is that a great deal of careful research needs to be done on all aspects of the fossil-fuel technologies that may contribute to long-range climate changes. While the possible influence of CO_2 has been rightly emphasized because of the prohibitive cost of its removal at the source, it is nevertheless apparent that the price exacted for replacement of fossil-fuel combustion would be so high that remedial measures of every conceivable variety merit coordinated emphasis.

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APPENDIX

Nomenclature

- A_e cross sectional area of the Earth $= \pi r_e^2$, cm^2
- k extinction coefficient due to particles in the atmosphere, cm^{-1}
- n particle number density, particles/cm^3
- N_p total number of particles
- m_p total particulate mass, g
- r_e earth radius $= 6.368 \times 10^8$ cm
- r_p particle radius, cm
- r_1 radial distance from the Earth's center to where particles are last encountered by solar radiation, cm
- r_2 radial distance from the Earth's center to where particles are first encountered by solar radiation, cm
- V volume into which particles are dispersed, cm^3
- β fractional decrease in solar radiation incident on the earth's surface
- ρ_p particle density, g/cm^3

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NOTE

A Low-Cost Technology for Increasing the Earth's Albedo to Mitigate Temperature Rises

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Abstract – We discuss a low-cost approach, first suggested in 1984, for possible mitigation of global warming through planetary albedo modification. Research problems that require study are emphasized in this discussion.

1. A Heretical View on the Issue of Atmospheric CO_2 Increase and Climate Change

In a recent paper, Nakićenović and Messner[1] discuss issues relating to CO_2 removal from the atmosphere and mitigating possible climate changes. In this connection, they quote calculations[2] published in 1984 showing that the conversion to small particulates of about 1% of the fuel used in normal commercial jet flights over the brief time span of 10 years would be sufficient to increase the planetary albedo by 2% and thereby counteract about a 3°C planetary temperature rise associated with the accumulation of atmospheric greenhouse gases (GHGs).

Since jet planes normally cruise above 30,000 ft, particle injection would occur directly into the lower stratosphere without a change of flight regimes. Furthermore, by appropriately adjusting the fuel-to-air mixture ratios, the particle sizes should be controllable. In the original two-part analysis,[2] a mean particle radius of 0.50 μm was first chosen and then an r^{-6} particle-size distribution with $r_{min} = 0.05$ μm and $r_{max} = 10$ μm was used; the particles were uniformly distributed between 40,000 and 100,000 ft in the first example and between 620 and 2500 ft in the second example. Small particles with radii below about 1 μm are expected to have long residence times at high altitudes and move with the mean air-stream velocities. Both calculations led to the conclusion that about 15×10^9 lbs of particles would be needed to increase the planetary albedo by 1% and thereby offset a 1.5°C GHG-induced temperature rise; about 30×10^9 lbs = 1.5×10^7 (short) tons of particles are needed to increase the planetary albedo by 2% and compensate for a GHG-induced temperature rise of about 3°C, which has been estimated to accompany doubling of the atmospheric CO_2 concentration.

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Since the expected residence times of very small particles in the lower stratosphere may be longer than 10 years, annual particle-injection rates of 7.5×10^5 tons for 10 years are needed to effect planetary atmospheric cooling of about 1.5°C whereas annual injection rates of 1.5×10^6 tons will counteract GHG-induced warming associated with doubling of the atmospheric CO_2 concentration.

According to data received from the American Petroleum Institute,[3] world-wide use of jet fuel during 1990 amounted to 3.776×10^6 bbl/day or about 2.00×10^8 tons/year. Thus, at 1% fuel conversion to particles, about 3.8 years would be required to reach the albedo increase and temperature reduction required to compensate for a 1.5°C rise caused by increasing the atmospheric CO_2 concentration. There is, of course, nothing sacrosanct about using carbon particles from incompletely burnt jet fuel to increase planetary scattering. An alternative approach might involve the use of a small amount of a fuel additive such as silane, which would be rapidly and completely converted to SiO_2 (sand) and water. It should not be very difficult to choose the combustion conditions so as to produce sand particles in the desired size range.

Without experimental studies, it is not possible to define precisely the dollar cost per metric ton of carbon mitigated. If the particles come from coal in a jet-fuel-coal mixture, the fuel cost would be less than 0.03 cent/t of C mitigated. For particle generation from jet fuel, the fuel cost may be up to about 7 times greater. For particle generation from an additive such as silane, the fuel cost might reach $0.05 per t of C mitigated, which still remains more than three orders of magnitude smaller than the lowest quoted source-removal costs for carbon dioxide. The specified cost estimates do not include small incremental allowances for handling and carrying fuel additive on normal jet flights.

Recent experience with particulate depositions following the Mount Pinatubo and other volcanic eruptions has yielded ambivalent data concerning environmental problems other than planetary cooling resulting from an increase in albedo.[4-6] Possible catalytic effects of particles in ozone depletion have been noted.[7] The issue raised in Ref. 2 that "the critical questions of particulate distribution and atmospheric residence time remain to be examined" suggests further analysis and possibly exploratory experiments with controlled amounts of particle injections.

With the possible availability of a low-cost technology for remediation of GHG-induced temperature rises, it would seem appropriate to delay implementation of drastic and excessively costly measures on CO_2 reduction. Furthermore, climate-modeling efforts should be pursued at levels that are commensurate with the likelihood that the outcome of a global experiment will become apparent before the modeling efforts yield predictions with sufficient certainty to justify drastic and excessively costly actions. This line of argument leads to the heretical views summarized in Table 1.

Table 1. A heretical view of the atmospheric CO_2 build-up issue.

The Conventional Wisdom	A Heretical View
1. Research on climate prediction is a high-priority necessity because it will yield results that are needed for long-range planning and near-term policy implementation.	1. Research on long-range climate prediction cannot yield believable results for policy planning because the modeling is and will remain incomplete. Thus, modeling must be viewed as an adjunct to a carefully conceived measurement program and should be pursued at a level commensurate with this limited objective.
2. Catastrophic climate changes are in the offing with unacceptable temperature rises and sea-level changes. After the fact, only the most heroic and costly measures will be available to return the planetary atmosphere to a proper balance. For these reasons, we must immediately implement global CO_2-reduction strategies even though the economic costs for implementing these reductions may be very high.	2. All of the conventional wisdom has large elements of uncertainty. If it really gets too hot, short-term measures at very low costs may become available to increase the planetary albedo by a few percent and thereby rapidly modify any excessive heating. One easily implemented and low-cost option involves combustion modifications of high-flying jet planes to produce increased particulate emissions at high altitudes. The increase in planetary albedo will offset GHG-induced heating.

The preceding comments should not be interpreted to mean that we support the idea of rapid and continuing fossil-fuel conversion to water and CO_2. Quite to the contrary, it is our view that there are compelling geopolitical, logistic and conservation arguments for replacing fossil-fuel use with deliberate speed and under non-crisis management conditions by cost-effective, renewable or nuclear energy-conversion technologies.

2. Independent Experimental Verification of Cooling

Experimental verification that increasing the planetary atmospheric reflection coefficient will lead to cooling is not needed in view of the abundance of pertinent data from past volcanic eruptions and from ground-based pollutant production.[4-7] However, verification that good control of particle distribution and stable management is possible over long periods of time is certainly required before this or any other large-scale experiment in geoengineering is implemented. Furthermore, the effects, if any, on stability of the ozone layer should be studied with particular reference to particle composition. The intensity of harmful uv radiation reaching the ground will be greatly reduced at short wavelengths because of backscattering from particles and its measurement should be an important component of field studies.

The two calculations performed in Ref. 2 verify the obvious fact that the altitudes where the particulate distributions are located are almost irrelevant insofar as total scattering is concerned. On the other hand, it is clear that the inert-particle residence times in the lower atmosphere where precipitation occurs will be much shorter than at higher elevations. Finally, there remain the all-important issues of mean particle-size selection, particle-size distributions, and field implementations. As noted, particles smaller than about 1 μm may be expected to move with the mean-stream velocities and have long residence times above about 40,000 ft.

It may be appropriate to perform a series of small-scale experiments during the next few decades. A useful experiment might be cooling during a hot summer day of a large metropolitan area that represents a local heat island and is blessed by nearby airports with heavy traffic. The primary reason for not selecting a location of this type is that all associated ground malfunctions, from heartburn to split nails, will be blamed by enthusiastic lawyers on the particle clouds. For this reason, it is preferable to begin with a large (e.g., 10 km by 10 km) uninhabited desert region over which heavy jet air traffic is normally routed. Early experiments should be conducted with particles that are sufficiently large to assure rapid fall-out. If no unexpected results occur, the region for particle seeding could be enlarged and the particle sizes reduced. Careful ground monitoring of solar radiation, temperatures, wind speeds, and precipitation should accompany a well-constructed modeling effort. This type of program, when pursued with the cooperation of transcontinental airline carriers, may well lead to results and verifications that should make the proposed "last resort" cooling program an *acceptable component of long-range planning* in dealing with the issue of global warming associated with anthropogenic modifications of atmospheric compositions. Full-scale implementation of geoengineering to counteract GHG emissions may actually never be needed and should not even be considered except as a possible last resort 50 to 100 years from now. In the meantime, a modest research effort to assure good control and more complete understanding of the scientific issues involved in modifying the earth's albedo should prove to be a useful adjunct to other current studies dealing with long-range climate changes.

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Emphasize this -- Many famous scientists have later copied this idea without acknowledgement of my 1992-93 Proposal.

A LOW-COST/NO-REGRETS VIEW OF GREENHOUSE-GAS EMISSIONS AND GLOBAL WARMING†

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A low-cost/no-regrets approach to the issue of global warming as the result of greenhouse-gas emissions has the following features: (i) minimal interference with the world's energy systems, (ii) careful study of unresolved scientific issues before implementation of costly controls, and (iii) if necessary, geoengineering to increase the earth's albedo 50 to 100 years from now by using known scattering data for small particles to implement a desired level of planetary cooling.

INTRODUCTION

Probably no incompletely understood scientific issue in human history has ever entered the political arena with the persuasive dedication of advocates who want to control greenhouse-gas emissions (GHGE) because of the threat of global warming (GW). As a result, we find politicians all over the world supporting strategies and measures designed to "save the planet" by proposing to expend huge sums of money in order to implement rapid changes in the world's energy-supply systems, which are the lifeblood of modern technologies and an essential requirement for improving human standards of living. The productive sides of the issue involve implementation of cost-effective energy-conservation measures, explorations of alternative energy technologies with the goal of replacing fossil-fuel technologies, and the widespread introduction of a new ethic to minimize the environmental impacts of growing human populations. Underemphasized in this debate are the crucial determinants of environmental changes defined by exponentially growing human populations with

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2. Abbreviations: DCs, developed countries; GHGE, greenhouse-gas emissions; GW, global warming; LDCs, less developed countries.

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exponentially growing needs for resources to accommodate more people with improving standards of living (Penner et al., 1992). Instead of emphasizing this last and most important problem, political emphasis has shifted to raising the issue of stabilizing atmospheric carbon dioxide levels to a latter-day religion but, unfortunately, without the needed firm scientific support to justify this fundamental diversion of effort.

The attraction of the CO_2-minimization issue as a political measure is easy to appreciate. Blame in the developed countries (DCs) and the onus for change is conveniently placed on the large and still prosperous energy sector, while environmental enthusiasts expose to politicians issues and plans that are largely beyond their quantitative comprehension. The governing bodies of the less developed countries (LDCs) cannot afford the luxury of escalating energy-supply costs and have therefore adopted the convenient strategy of asking for tributes from the DCs in return for the unsubstantiated promise that their energy-policy actions will be less damaging to the global environment than those pursued in the DCs. This composite effort has become a large and costly scientific and political enterprise with more fervor than fact to support itself in terms of an elusive averted evil which, it is stated, will surely befall the planet without "no regrets" CO_2-stabilization programs.

The issue of CO_2 stabilization is further confused by the divergent opinions of top-down economists (who use historical projections to estimate the costs of CO_2-stabilization programs) and bottom-up engineers (who base highly optimistic prognoses of zero- or even negative-cost stabilization programs on the hypothesis that the "best" technologies will become near-term market successes). The bottom-up experts seem to forget that only very few promising inventions actually succeed in the marketplace. The top-down economists also could be wrong if an entirely new technology (e.g., fuel cells with doubled conversion efficiencies of fuel energy to electricity) were to become cost-competitive and were to enter the market over a reasonably short time span (15 to 20 years) at a significant scale.

Unfortunately for the cause of the CO_2-stabilization programs, the needed scientific consensus to pursue the presently advocated course of action has not evolved. Persistent and careful scientific analyses correlate observations of what global warming during the last century with changes in solar activity (Friis-Christensen, 1993). The originally predicted disastrous sea-level rises accompanying GW have shrunk with time and are being replaced by estimates that the dominant past and presumably future sea-level changes are caused by changes in plate tectonics (Emery and Aubrey, 1993). Most important is the persistent and recurring debate that the well defined escalation of atmospheric CO_2 concentrations is the result natural phenomena that are not understood which happen to coincide with anthropogenic CO_2 additions resulting from fossil-fuel burning and global deforestation (Wuebbel and Edmonds, 1991; Starr, 1993). A careful examination of atmospheric CO_2 residence times has been used recently by Starr (1993) to suggest that only about 20% of the measured atmospheric CO_2-concentration rise is attributable to anthropogenic fossil-fuel sources.

These varied expressions of doubt will have the inevitable effect of weakening the political will to implement large-scale anthropogenic reductions in GHGE once associated large costs have been ascertained. The payments of tributes from the DCs to the LDCs are not likely to materialize. In the end, it will become more convenient for politicians to talk and do nothing than to expend funds that do not show near-term and perhaps also not long-term benefits for their constituents.

What is the proper course of action in this climate of uncertainty? If the doubters are right, GHG concentrations will escalate regardless of what is done in the name of atmospheric CO_2-stabilization. If the doubters are wrong, their persistence will nevertheless undermine political action to the point where expenditures are not likely to be made to a sufficient degree to reverse GHGE. It thus appears likely that, in either case, we may face a planetary atmosphere with greatly increased CO_2 concentrations 50 to 100 years in the future. At this point, drastic remedial measures involving geoengineering may well be considered to constitute justifiable measures.

CURRENT AND CONTINUING EXPERIMENTS AND MODELING OF PLANETARY COOLING

Real (not computer) experiments to effect global cooling are being performed with each volcanic eruption. Far too little is known about the particle-size distributions, chemical compositions, atmospheric penetrations, and other quantitative features of these phenomena. On the other hand, radiative flux measurements obtained in NASA's Earth Radiation Budget Experiment clearly show the expected planetary cooling following the Mount Pinatubo eruption of June 1991 (Minnis et al., 1993). Strong global cooling was observed immediately and increased through September 1991. As expected, aerosols caused direct increases in the albedo over clear regions and both direct and indirect albedo increases in cloudy regions.

Many volcanic eruptions will occur between now and the year 2050. Careful measurements, coupled with an appropriately detailed modeling effort, should provide the necessary competence for quantitative predictions of the effects of anthropogenic atmospheric particle loading within half a century. At this time or later, it should therefore become feasible to implement human control over the earth's albedo for the purpose of implementing global cooling, if it is deemed desirable to do so.

A LOW-COST IMPLEMENTATION TECHNIQUE FOR CONTROLLED ALBEDO INCREASES BY 2050 OR LATER

Approximate scattering calculations show that conversion of about 2% of the jet fuel used in 3.8 years (at the 1990 consumption level for air transport) to small particles of appropriately selected radii will increase the earth's albedo sufficiently to counteract a 3°C temperature rise caused by the doubling of GHGs above pre-industrial levels (Penner et al., 1984). By 2050, jet transport may be expected to increase significantly (a 2%/y increase for 55 years will increase the total jet fuel used by about a factor of three), i.e., by 2050, little more than a one-year conversion schedule of 2% of the jet fuel used should be sufficient to provide the needed albedo change to counteract doubling of GHGs. Furthermore by 2050, it is reasonable to expect that the then current generation of jet-transport planes will have greatly increased carrying capacity and will fly at supersonic speeds at substantially increased altitudes, thereby allowing direct particulate injections well above the region where particle removal through precipitation is an important factor. The stratosphere from 60,000 to 100,000 ft may be a preferred region for particulate dispersals (Penner et al., 1984).

Estimated Fuel Costs Associated with this Program (Penner and Haraden, 1993)
The total mass of the earth's atmosphere is 5.12×10^{15} mt. If the pre-industrial CO_2 concentration was 220×10^{-6} mole of CO_2 per mole of air, then the pre-industrial era atmospheric CO_2 mass was 5.12×10^{15} mt $\times 220 \times 10^{-6} \times (44/29) = 1.71 \times 10^{12}$ mt of CO_2 or $1.71 \times 10^{12} \times (12/44)$ mt of C = 4.66×10^{11} mt of C.

If we follow the conventional wisdom that 45% of the emitted anthropogenic CO_2 remains in the atmosphere, doubling of the atmospheric CO_2 concentration corresponds to the mitigation of $4.66 \times 10^{11} \times (1/0.45)$ mt of C = 1.04×10^{12} mt of C.

Complete cost estimates will require experimental studies. Since aircraft normally have reserve weight-capacity margins well above 2% of the fuel weight, it is reasonable to assume that the total mission cost will not exceed the cost of fuel converted to particulates by more than a factor k with k, in the range of 2 to 3. If the particles are made from coal in a jet-fuel-coal mixture, coal costs \$20/ton, and a 1.5°C temperature rise is to be mitigated by producing 15×10^6 tons of small particles, then the fuel cost of the distributed particles in 15×10^6t × \$20/t = \$3 × 10^8, i.e., the fuel cost per ton of carbon mitigated becomes \$3 × $10^8/(1.04 \times 10^{12} \times 1.1)$ton = \$3 × 10^{-4}/ton, corresponding to a mission cost of \$3k × 10^{-4}/ton of C mitigated or less than 0.1 cent/ton of C mitigated.

Similarly, if the particles are formed from a fuel-rich jet-fuel-air mixture with jet fuel costing \$20/barrel or about \$150/ton, the previous cost estimate is increased by about a factor of 7.5 and the mitigation cost remains below 1 cent/ton of C. Finally, it may be desirable to form the particles as relatively inert SiO_2 by using a silane (SiH_4) admixture that is readily converted to SiO_2 and water. This approach might raise the mission cost to the range of 10 cents per ton of C mitigated.

We conclude that the use of particulates in the atmosphere to increase the earth's albedo will have costs that are at least three orders of magnitude smaller than carbon-mitigation costs using source removal of CO_2 or carbon taxes to reduce fossil-fuel utilization through conservation or fuel-switching measures (based on top-down costing) (Penner and Haraden, 1993).

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ENVIRONMENTAL IMPACTS OF STRATOSPHERIC PARTICULATE CONCENTRATIONS

The precise definition of environmental impacts, other than albedo augmentation, caused by stratospheric particulate distributions is an essential component of the research programs that should be actively pursued during the next half century before man-made climate changes are implemented through geoengineering measures. It has been suggested that small particles serve as catalytic surfaces in reaction processes involving chlorofluorocarbons and ozone that may be responsible for depleting the ozone layer (Minnis et al., 1993). These processes should become progressively less important as the chlorofluorocarbons are replaced as refrigerants and depleted from the stratosphere during the next century. Furthermore, surface-catalytic processes of the type identified are strongly dependent on the nature and structure of the surface involved. For this reason, it may become advantageous to create particle clouds in the form of sub-micron sand particles by using SiH_4 as a fuel additive.

In conclusion, we note the possibility that another important geoengineering project may be worth launching after careful study. Thus, if ozone depletion of the stratosphere becomes important and is accompanied by a substantial increase of short-wavelength ultraviolet radiation near the earth's surface (for which there is no experimental evidence at present), the injection of very small particles may be needed to reintroduce an efficacious ultraviolet shield to protect man and other creatures who require this type of protection.

For the best of all possible outcomes, ground-based adaptation and technology modifications may prove to be sufficient to protect the planet while a cost-effective change from fossil-fuel to renewable energy is implemented during the next half century. For intolerable warming, low-cost planetary albedo augmentation may become the methodology of choice some decades in the future.

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Block That Sun

Before S. S. Penner retired from the University of California at San Diego, he was for two decades the director of its Energy Center. A chemist and an aeronautical engineer, he was also a prolific chairman of government committees, many of them having to do with how best to burn fossil fuels. In 1983, when Penner was invited to give a paper at an astronautical conference on some socially useful application of aircraft or satellites, global warming was beginning to be talked about a lot. A solution to that, Penner decided, would certainly be useful.

He considered first the possibility of putting 9 million 2,000-foot-wide Mylar balloons into orbit to block some sunlight. But a back-of-the-envelope calculation told him that the launch cost alone would run to $315 trillion. So Penner started to think smaller. Another quick calculation told him that if you used half-micron particles as reflectors, it would take surprisingly few of them to offset the greenhouse effect caused by a doubling of CO_2—only about 15 million tons spread over the whole planet. If you put particles that small in the stratosphere, between 40,000 and 100,000 feet, they would stay up there for decades, Penner figured. His idea for how to get them there was downright elegant (at least compared with firing dust salvos at the stratosphere with battleships): if you just adjusted all the jet engines in the world so they burned a little richer and emitted 1 percent of their fuel as tiny particles of soot, you'd get your 15 million tons' worth. The cost would be derisory. "And you'd hardly know that the particles were there," says Penner.

Unfortunately, commercial jets don't spend much time above 40,000 feet; Penner now says he has in mind a twenty-first-century world crisscrossed by high-flying SSTs. And particles don't stay in the stratosphere as long as Penner assumed, so canceling all of global warming wouldn't be quite as cheap or easy as he figured. The eruption of Mount Pinatubo in 1991 shot a sulfurous plume up to 70,000 feet—but within three years even the smallest sulfate particles had fallen to Earth.

On the other hand, Pinatubo did cool the planet—by nearly a degree Fahrenheit, at least in the tropics. "If you had a volcano like Pinatubo going off every two years, you would be completely offsetting CO_2 warming," says V. Ramaswamy, a climate modeler at the Geophysical Fluid Dynamics Laboratory in Princeton. But that doesn't mean we know yet how to do what the volcano did. The problem is not just the potential side effects of a stratospheric parasol—the particles might help destroy ozone—it's that even the effects on climate are uncertain. Putting jet soot into the stratosphere would block sunlight, but what would happen as the particles settled into the zone of clouds? A recent NASA study showed that jet contrails evolve into cirrus clouds as water droplets freeze around the sulfate and soot particles. Cirrus clouds, however, actually warm the planet—they bounce more heat back to Earth than sunlight to space. So sootier jet exhaust would not necessarily be a good thing.

Still, the basic idea—that it might be possible to cool the planet by scattering particles in the atmosphere—"is not entirely wacky," as Ramaswamy puts it. A particle screen would certainly be cheap, and it could be dismantled quickly—by letting the particles fall to Earth—if things went awry. Many of the unanswered questions about it are ones climatologists are trying to answer anyway. But a focused look into the geoengineering possibilities would seem prudent. "There has been no research program on this activity," says Penner. "People are very reluctant to do this—and I think rightly. But I wasn't saying go out and do this. I was saying go out and study this."

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Dam That Sea

To Robert Johnson, a prudent hedge against climate disaster would be to start work on a dam across the Strait of Gibraltar, right now. Even before retiring from the Honeywell Corporation, where he spent a career working on physics problems related to heating and cooling buildings, Johnson had an interest in global climate control too. An adjunct professor at the University of Minnesota—a state that was once submerged under a thick sheet of ice—Johnson thinks an ice age could start again soon, as a result of global warming and the construction of the Aswān High Dam in