GLOBAL CLIMATE CHANGE CONTROL: IS THERE A BETTER STRATEGY THAN REDUCING GREENHOUSE GAS EMISSIONS?

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This Article identifies four major global climate change problems, analyzes whether the most prominent of the greenhouse gas (GHG) control proposals is likely to be either effective or efficient in solving each of the problems, and then extensively analyzes both management and technological alternatives to the proposals. Efforts to reduce emissions of GHGs, such as carbon dioxide, in a decentralized way or even in a few countries (such as the United States or under the Kyoto Protocol) without equivalent actions by all the other countries of the world, particularly the most rapidly growing ones, cannot realistically achieve the temperature change limits most emission control advocates believe are necessary to avoid dangerous climatic changes, and would be unlikely to do so even with the cooperation of these other countries. This Article concludes that the most effective and efficient solution would be to use a concept long proven by nature to reduce the radiation reaching the earth by adding particles optimized for this purpose to the stratosphere to scatter a small portion of the incoming sunlight back into space, as well as to undertake a new effort to better understand and reduce ocean acidification. Current temperature change goals could be quickly achieved by stratospheric scattering at a very modest cost without the need for costly adaptation, human lifestyle changes, or the general public's active cooperation, all required by rigorous emission controls. Although stratospheric scattering would not reduce ocean acidification, for which several remedies are explored in this Article, it appears to be the most effective and efficient first step toward global climate change control. Stratospheric scattering is not currently being pursued or even developed, however; such development is particularly needed to verify the lack of significant adverse environmental effects of this remedy. Reducing GHG emissions to the extent proposed by advocates,

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even if achievable, would cost many trillions of dollars, and is best viewed as a last resort rather than the preferred strategy.

I. INTRODUCTION

As of late 2006, many environmentalists, some developed nations, and the State of California appear to have concluded that there is one climate change problem, global warming, and that there is only one solution to it: reducing emissions of greenhouse gas (GHGs), such as carbon dioxide, usually in accordance with the Kyoto Protocol[1] or similar decarbonization approaches. This Article asks whether there are other related problems and other solutions to climate change that would be more effective and efficient, and, if so, what they might be. The problem is potentially so important to the future of humans on Earth, and the proposed solution is so expensive, that it is vital to carefully examine whether reducing GHGs really is the best strategy before any solution is implemented. Yet to date there has been surprisingly little analysis of this issue.

The standard response to most pollution problems has been to impose regulations limiting the production and/or discharge of the pollutants involved, in this case GHGs. This regulatory approach has been the basis for most of the discussions of global warming as well, and underlies the major current efforts represented by the Kyoto Protocol and other proposals for controlling GHG emissions. Economists have suggested that a more economically efficient approach would be

[1] Kyoto Protocol to the United Nations Framework Convention on Climate Change, Dec. 10, 1997, *available at* http://unfccc.int/resource/docs/convkp/kpeng.pdf [hereinafter Kyoto Protocol].

to provide economic incentives to reduce discharges, and this approach has generally been accepted by proponents of GHG control, perhaps in recognition of the very high costs involved in GHG reduction. This pollutant mitigation approach to global warming assumes that if somehow human-induced pollution (in this case GHGs) could be reduced or eliminated, then all of Earth's climate change problems would be solved. This Article examines whether this underlying assumption is incorrect and whether the current Kyoto appraoch is likely to reduce GHG emissions to "nondangerous" levels.

Humans have embarked on an inadvertent and potentially very risky experiment involving rapidly increasing GHG levels in the atmosphere. The question examined here is not whether the experiment is taking place or the degree of control that might be required, but rather whether there are efficient and effective remedies for global climate change problems and what they might be. Because of the extreme complexity of the problem and the number of disciplines that need to be involved in defining a practical solution, the analysis must necessarily be equally complicated and broadly based. Unfortunately, the few previous analyses have ignored the reality that any remedies adopted, if they are to be successful, must not only be technically sound but also economically and politically feasible. Although the emphasis in this Article will be on economics, a serious attempt has been made to consider all the other factors that need to be taken into account to find a workable solution to what may be the most difficult environmental problem that modern humans have faced.

One of the major difficulties in solving climate change problems results from the fact that no one has really leveled with the public as to how difficult it would be to achieve the goals that the advocates of emissions control believe are necessary. This may entice the public to embrace particular solutions to the problem, but in the longer run may result in major problems for implementing these solutions as it becomes clearer what is really involved. It seems better to outline the full difficulties involved and then attempt to find the best available solutions. That is the goal of this Article.

Others have called for an objective analysis of available technological options to solve climate change problems. Braden Allenby expressed this as follows in a recent report from the National Academy of Engineering:

> The current approach to global climate change carries within it not just policies, but also a vision, a teleology of the world that is, in important ways, both unexpressed and exclusionary. Perhaps for this reason,

> the role of technology has been relatively ignored throughout the negotiating process and, when it has come up, has been quickly marginalized.
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> In fact, there are many possible technologies that might reduce carbon loading in the atmosphere, but many of the most important ones are out of favor. For example, nuclear energy has been excluded by general agreement, and geoengineering (e.g., aluminum balloons in the stratosphere to reduce incoming energy to the atmosphere) has been shunted aside, regarded as the dream of a few eccentrics. Biotechnology to improve agricultural efficiency and biological carbon sequestration are clearly not acceptable to many participants in the Kyoto process, and to many environmentalists generally. The rejection of these and other technologies tends to reinforce the impression that the Kyoto process is an exercise in social engineering by Europe targeted at the United States. Regardless of the truth, this impression is obviously conducive to conflict and deadlock (as indeed has happened). . . .
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> A useful process that would contribute significantly to the rational, ethical management of the future would be to categorize technological possibilities and determine, as objectively as we can, their risks and benefits and the optimal scale for each. We could then develop a portfolio of options for future negotiations. Technology, especially in emotionally and ideologically charged environmental debates, almost never provides complete answers. But an array of technological options enables choice and thus increases the chances that we will be able to balance the disparate values, ethics, and design objectives and constraints implicit in the climate change discourse. Technology may help us respond to the world we are creating in responsible, ethical, and rational ways.[2]

A good example of what Allenby appears to be talking about in his second paragraph above, concerning the rejection of new technology, is provided by the recent *Stern Review*[3] in Great Britain, which reviewed the economics of climate change. The *Stern Review* never uses the word geoengineering, which is the term often used for many of the global technological solutions to the problem, and reaches radically different conclusions from this Article. The *Review* enumerates numerous benefits (*B*) from controlling GHGs and argues that the costs of control (*C*) would be less than the costs of global warming.[4] But if,

[2] Braden R. Allenby, *Global Climate Change and the Anthropogenic Earth, in* NAT'L ACAD. ENG'G, NAT'L RES. COUNCIL, THE CARBON DIOXIDE DILEMMA: PROMISING TECHNOLOGIES AND POLICIES 3, 8-10 (2003), *available at* http://www.nap.edu/catalog/10798.html (citations omitted).

[3] NICHOLAS STERN, STERN REVIEW: THE ECONOMICS OF CLIMATE CHANGE 1-61 (2007), HM Treasury, United Kingdom. A prepublication version of the *Stern Review* is available at http://www.hmtreasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

[4] *Id.*

as argued in this Article, most of the claimed benefits (*B*) can be obtained for a cost many orders of magnitude less than *C* (say *C*/4000 for the sake of discussion) by using engineered climate selection, humans would be foolish to pay the much higher cost *C*. Listing all the components of *B* and comparing them to *C* does not change this reality. Other reviewers have raised other concerns regarding the *Review*.[5]

Allenby's call for a reexamination of geoengineering approaches has recently been reinforced by a number of other prominent scientists who have supported the use of geoengineering approaches for global climate change control.[6]

This Article first analyzes whether the most prominent of the GHG approaches is likely to be either effective or efficient in solving the global warming problem as defined by the advocates of GHG controls, and then analyzes several management and technological alternatives. This Article assumes that recent predictions as to the effects of GHG emissions on climate by proponents of GHG control are broadly correct and will not discuss the reasons for believing that warming is or is not currently occurring. It will further assume that the degree of GHG control required for controlling global warming advocated by GHG control proponents is also correct. Rather, the purpose of this Article is to ask what the climate change problems are, whether the Kyoto Protocol and other decarbonization approaches are the most useful tool for solving them, and what other approaches might be more efficient and effective.

This Article takes a broad view of the issue not only by looking at a broad range of climate change problems and the management and technological options for their solution, such as Allenby suggests, but also by viewing climate change in the larger context of both short- and

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[5] *See, e.g.*, *Shots Across the Stern*, ECONOMIST, Dec. 16, 2006, at 80, 80 (discussing criticisms of the *Stern Review*'s emphasis of the "welfare of future generations" and "consumption of the rich relative to that of the poor").

[6] *See* Oliver Morton, *Is This What It Takes to Save the World?,* 447 NATURE 132-36 (2007); P.J. Crutzen, *Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution To Resolve a Policy Dilemma?,* 7 CLIMATIC CHANGE 211 (2006) (advocating placing reflective particles in the stratosphere as more cost effective than reducing GHGs); T.M.L. Wigley, *A Combined Mitigation/Geoengineering Approach to Climate Stabilization*, 314 SCIENCE 452, (2006) (urging a combined GHG reduction with geoengineering approaches to combat both climate change and ocean acidity); William J. Broad, *How To Cool a Planet (Maybe)*, N.Y. TIMES, June 27, 2006, at F1 (discussing proposals to rearrange the earth's environment on a large scale, including cooling the planet by injecting sulfur into the stratosphere); Charles J. Hanley, *Could Smog Protect Against Global Warming?*, SEATTLE TIMES, Nov. 16, 2006, *available at* http://seattletimes.nwsource.com/html/nationworld/2003433914_webwarming16.html.

long-term effects of natural forces and human activities on climate. This Article argues that it is particularly important to consider the practical implications of attempting to implement a variety of management and technological options in terms of the psychological and political changes that would be required. Climate history is considered over the last three million years, since the beginning of the current chapter in Earth's history, rather than the last hundred years or even the current Holocene Epoch, which is the focus of most discussions on climate policy.

A. *Needed Characteristics of Approaches Used To Control Climate Change*

Joseph Aldy et al. recently enumerated six criteria to "guide an assessment of proposed global climate policy regimes: (1) the environmental outcome; (2) dynamic efficiency; (3) dynamic cost-effectiveness; (4) distributional equity . . . ; (5) flexibility in the presence of new information; and (6) participation and compliance."[7] Except for the addition of a seventh and an eighth criteria, the criteria proposed in this Part are very similar to those, so substantial added justification and detail concerning the first six criteria can be found in the article by Aldy et al., with one exception: criterion five has been made much more specific because of the broader perspective taken in this Article toward the range of climate change situations that may require attention. The seventh criterion may be captured by criteria two and three because such risks have economic costs, but since these risks are usually poorly understood and therefore very difficult to quantify, it appears better to make this an added criterion. The eighth is an "other" category needed for a more general comparison of the proposals.

(1) *Effective environmental outcome*: Will implementing the management tool or remedy result in the desired climate management in a timely manner? Remedies that are not effective can be worse than no remedy, since people may believe that a problem is being solved when it is not. Where applicable, effectiveness in controlling global warming will be measured in terms of the likelihood that the European Union/United Nations Framework for Convention on Climate

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[7] *See* Joseph E. Aldy, Scott Barrett & Robert N. Stavins, *Thirteen Plus One: A Comparison of Global Climate Policy Architectures*, 3 CLIMATE POL'Y 373, 374-79 (2003).

Change 2°C maximum temperature change goal[8] will not be exceeded (discussed below in Part III.B), since that is the goal promoted by most GHG control advocates.

(2) *Economic feasibility*: Will implementing the management tool or remedy produce positive net economic benefits? Remedies that do not will decrease overall human economic welfare.

(3) *Cost-effectivenes:* In the case of global average temperature change, what is the cost-effectiveness of the management tool or remedy in terms (more specifically) of (3a), its long-term marginal cost expressed in dollars per ton carbon of CO2 emissions mitigated? All other things equal, remedies that can achieve a given goal (in this case a given level of CO_2 emissions) at lower cost are preferable to those that achieve them at a higher cost. Marginal costs measure the cost of the last and presumably most expensive project that would be undertaken using a given remedy and facilitate comparisons with the alternatives and with estimates of the economic benefits to be achieved. Where there is little variation between the cost of projects per unit of emissions reduction, this distinction concerning marginal costs is of little importance. But where there is a broad range, this is important. Obviously there are also opportunities for controlling other GHG emissions, but it is assumed here that CO_2 emissions control is broadly representative of those available for other GHG emissions in terms of the broad remedies or tools available for doing so. As discussed in Part V.F, *infra*, not all the remedies discussed produce exactly the same benefits. This makes cost-effectiveness comparisons a little dangerous, but I believe still useful in comparing the remedies if these differences are kept in mind.

(4) *Improved distributional equity*: What is the impact of the management tool or remedy in terms of its impact on various human income groups or nations? Remedies that improve distributional equity would appear to be preferable to those that do not.

(5) *Provide policy flexibility*: If conditions change, how easily and how rapidly can the management tool or remedy being pursued be changed to meet the new conditions? Because natural climate changes may occur abruptly, particularly during periods of climate transition, major volcanic eruptions, or nuclear conflicts, and because of the substantial uncertainties involved, a static approach that is diffi-

[8] European Environment Agency, *CSI 013 Specification: Atmospheric Greenhouse Gas Concentrations*, http://themes.eea.europa.eu/IMS/ISpecs/ISpecification20041007131717/guide_summary_plus_public (last visited May 1, 2007).

cult to change in a relatively short timeframe will be much less useful than a more flexible one. There are at least three important aspects of flexibility in the context of climate change. The first (*5a*) is the ability to alter the pace of implementation of a remedy being considered as needed to meet changing conditions. The second (*5b*) is the capability to deal with global cooling as well as global warming if conditions change or a major volcanic eruption results in rapid cooling. A third aspect (*5c*) is the ability to deal with global temperature distribution. As discussed in Part II, global warming and to some extent cooling represent real risks for Spaceship Earth and its living cargo. Given the reality of long lead times for changing the atmospheric levels of GHGs and given the less than overwhelming correlation between these levels and global temperatures, it would appear that a faster-acting, more effective, lower-cost, and quickly reversible approach is much to be preferred in any attempt to influence global temperatures.

(6) *Not place undue demands on participation and compliance*: Does the management tool or remedy require widespread active participation and compliance to be successful? How likely is that to occur? Greater such demands reduce the likelihood of successful implementation of a management tool or remedy.

(7) *Not pose other major environmental risks or provide other environmental benefits*: Does the management tool or remedy create other environmental risks unrelated to climate control? If the remedy poses a significant risk of creating other environmental risks, the world may not be better off as a result of using it. Or are there other environmental benefits?

(8) *Have other important favorable or unfavorable characteristics*: Are there other important advantages or drawbacks to the proposed management tool or remedy not already discussed?

B. *What Are the Problems?*

Although the problems posed by climate change are often considered to be a single problem (usually referred to as global warming) with a single solution (reducing GHG emissions), they can more usefully be viewed as four interrelated problems (shown in Tables 1 and 1a in the Appendix) that have both human and natural origins since the effects of and solutions to these problems are significantly different. Conclusions concerning effective and efficient control measures for each problem can be found in Part V.F, *infra*. The four problems are:

(*P1*) The general trend of global temperatures is currently a gradual increase, and this appears likely to continue for the foreseeable future (discussed further in Part II, *infra*). This gives rise to most of the identifiable adverse effects usually mentioned as the results of global warming, including sea level rise, Arctic thawing, and possibly increased hurricane strength, among others.

(*P2*) Changes in atmospheric levels of GHGs have other nontemperature-related effects. In some cases these are believed to be positive, but at least one of them, ocean acidification, appears to have important adverse effects. There may be other such adverse effects that are not yet known.

(*P3*) There is an increasing risk that climate changes will trigger various "tipping points," where some believe that there will be particularly adverse feedbacks or other abrupt climate changes from continued global warming; some of these changes may be of a catastrophic nature. There may also be other natural events that will result in abrupt climate changes as well. A brief discussion of the scientific aspects of these effects can be found in Part II.F, *infra*.

(*P4*) There will almost certainly be shorter-term episodes of global cooling resulting from major volcanic eruptions and possibly from other natural causes as well as possible nuclear conflicts. In the twentieth century such volcanic eruptions occurred on average about once a decade and had significant, but not overwhelming, adverse effects. In the extreme case, however, a few of these episodes have in the past and are practically certain at some point in the future to be catastrophic to humans and to much of life on Earth. It is also likely that any nuclear conflict, even a regional one, would have similar effects. A brief discussion of the scientific aspects of these effects can be found in Part II.G, *infra*.

It is important to emphasize that the risks posed by each of these problems are different in magnitude, timing, and likelihood, so they are not directly comparable with each other. But they all impose risks and have potential adverse effects.

C. *What Are the Solutions?*

One of the primary purposes of this Article is to examine some of the major available remedies, approaches, and tools for climate control using the criteria discussed in Part I.A. These approaches can be divided into two general types: management and technological. In a number of ways these two approaches are parallel and either one could be used. In an attempt to simplify this confusing situation, however, this Article combines the two approaches primarily on the basis of the management approaches (*MA*s) but with some aspects of the technological approaches (*TA*s).

1. Management Approaches

There are at least four general approaches to how humans could "manage" these problems, with several sub-scenarios based on different assumptions:

- (*MA1*) Nonstabilized "business-as-usual" carbonization and adaptation;
- (*MA2*) Regulatory decarbonization;
- (*MA2a*) Kyoto and possible follow-ons;
- (*MA2b*) Decentralized;
- (*MA2c*) Liability based;
- (*MA3*) Engineering projects to directly change temperatures or atmospheric GHG levels;
- (*MA4*) International approach using all available technologies and approaches.

a. *(*MA1*) Nonstabilized "Business-as-Usual" Carbonization and Adaptation*

This management approach assumes that fossil fuel use and GHG releases continue at roughly the same rate as in recent decades in countries other than the participating Annex I nations to the Kyoto Protocol. This means that atmospheric levels of CO_2 would continue to increase at roughly two to three parts per million by volume (ppmv) per year.[9] This approach corresponds to remedy A in Parts IV and V and Table 2. A variation on this management approach (*MA1a*) is the increased use of public information and education campaigns to encourage people, companies, and governments to voluntarily reduce energy use or to reduce GHG emissions resulting from

[9] David Adam, *Surge in Carbon Levels Raises Fears of Runaway Warming*, GUARDIAN UNLIMITED (London), Jan. 19, 2007, *available at* http://environment.guardian.co.uk/climatechange/story/0,,1994071,00.html (reporting that from 1970 to 2000, CO_2 concentrations increased by about 1.5 ppm each year, from 2001 to 2005 they increased by an average of 2.2 ppm each year, and in 2006 by 2.6 ppm).

its use. This variation will be referred to as *MA1a* and will be discussed further in Part V.E.1.

b. *(*MA2*) Regulatory Decarbonization*

This management approach assumes that governments use their regulatory powers, such as executive actions or judicial decisions, to decrease GHG emissions compared to what they otherwise would have been, but do not assume direct responsibility for management of world climate. Since most of the actions would presumably be centered on reducing GHG levels, and most GHGs contain carbon, the approach is characterized as "decarbonization." The approach could be described as "coercive" because the governments involved would have to find ways and means to actively encourage their citizens and economic units to decrease GHG emissions or to penalize those that did not.

i. (*MA2a*) Kyoto Protocol and Possible Follow-ons

This management approach assumes that the world attempts to implement the Kyoto Protocol and that similar follow-ons to it are eventually negotiated. Since this is the most prominent of the decarbonization alternatives, it will be discussed at some length in Part III and analyzed primarily under Remedy *B* in Parts IV and V and Tables 1, 1a, and 2. The Protocol allows use of certain of the technological approaches that can also be used under *MA3*.

ii. (*MA2b*) Decentralized Approaches

This management approach assumes that governmental decarbonization takes a more decentralized approach. It assumes that various local or subnational governments take action other than through the use of liability laws to limit GHG emissions or force one or more unwilling national government to do so using existing laws. Examples include California's recent enactment of laws limiting emissions of GHGs[10] and the case of *Massachusetts v. EPA*.[11] Alternatively, it as-

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[10] California Global Warming Solutions Act of 2006, CAL. HEALTH & SAFETY CODE §§ 38500-385710 (West 2007).

[11] 127 S. Ct. 1438 (2007) (holding that state government plaintiffs did have standing to challenge the EPA's assertion that it does not have authority to regulate the emissions of GHGs associated with climate change); s*ee also* Massachusetts v. EPA, 74 U.S.L.W. 3713 (U.S. 2006) (No. 05-1120) (addressing the question of whether the

sumes that one or a few nations decide to pursue an approach that is broadly consistent with the Kyoto Protocol but independent of actions taken by any international body and uncoordinated with the actions of a group of nations with significant emissions. Such legislative actions have been proposed at the national level in the United States[12] and appear to be the objective being pursued by many U.S. environmental organizations. This approach will be considered as a subcase of *MA2a* and will be analyzed in Part V.E.2.

iii. (*MA2c*) Liability-Based Approaches

This management approach assumes that "tobacco-style" liability cases are successfully used to force major GHG emitters or manufacturers of GHG-emitting equipment to reduce emissions in one or more countries. The State of California, for example, has recently filed suit against the six largest automakers asking that they pay damages for the GHGs that their vehicles emit.[13] This will also be considered as a subcase of *MA2a* and will be analyzed in Part V.E.3.

c. (MA3*) Engineering Projects To Directly Change Temperatures or Atmospheric GHG Levels*

This management approach, sometimes referred to as geoengineering, assumes that one or more governments, or an international governmental body with the economic and technological resources to do so, select and implement engineering projects to directly change temperature regimes or atmospheric GHG levels for the world. These projects may or may not involve decarbonization. In the case of engineered climate selection, use of this technology does not receive any credit under the Kyoto Protocol.[14] Although international cooperation and coordination would be desirable, one nation could theoreti-

"EPA administrator ha[s] authority to regulate carbon dioxide and other air pollutants associated with climate change").

[12] *See, e.g.*, Safe Climate Act of 2006, H.R. 5642 109th Cong. (2006); Global Warming Pollution Reduction Act, S. 3698, 109th Cong. (2006).

[13] Nick Bunkley, *California Sues 6 Automakers over Global Warming*, N.Y. TIMES, Sept. 21, 2006, at C2.

[14] The Kyoto Protocol requires that Annex I nations reduce their emissions of GHGs. Such reductions are not required under engineered climate selection so countries would not recieve "credit" for such efforts. Kyoto does have some provisons allowing credit for carbon sequestration under some circumstances. It contains no such provisons for TA3 approaches (defined in Part I.C.2 infra) such as engineered climate selection.

cally carry out a program to engineer temperatures or GHG levels for the whole world, although probably facing great condemnation from other countries.

d. (MA4*) International Approach Including Use of All Available Technologies and Approaches*

This option is a hypothetical new international approach utilizing the best features of all the other management approaches. It would use all available technologies and include all sources of GHG emissions, but would apply a better rationale based on relative responsibility for the problem and the "polluter pays" principle to determine the costs to each country. One possibility would be the creation of a mandatory international fund based on past and present emissions.[15] This is intended as something of an "ideal" approach that solves some of the major problems with Kyoto while also providing an international framework for coordinated reductions in GHG emissions. This approach will be analyzed in Part V.E.4.

2. Technological Approaches

At the risk of some minor oversimplification, there would appear to be only three general technological approaches for controlling Earth's temperature climate:

Alter world atmospheric GHG levels by

- (*TA2a*) Changing GHG emissions (referred to here as "conventional approaches" or "conventional decarbonization" and discussed in Row B of Tables 1, 1a. and 2),
- (*TA2b*) Removing or sequestering GHGs already in or about to enter the atmosphere (referred to in this Article as "nonconventional decarbonization" and discussed in Part IV.C.1, *infra*, and in Row C of Tables 1 and 1a and Rows C through E of Table 2),

or

- (*TA3*) Altering Earth's radiation balance through other means (referred to as "engineered climate selection" or "radiative forcing," or "solar radiation management" and discussed in

[15] One recent suggestion along these lines has been made by Jagdish Bhagwati, *A Global Warming Fund Could Succeed Where Kyoto Failed*, FIN. TIMES, Aug. 16, 2006, at 13, *available at* http://www.ft.com/cms/s/7849f5b2-2cc3-11db-9845-0000779e2340.html.

Part IV.C.2 and Row G of Tables 1 and 1a and Rows F, G, and H of Table 2).

The first two technological approaches (*TA2a* and *TA2b*) will be referred to as decarbonization. The last two (*TA2b* and *TA3*) will be defined as nonconventional or geoengineering approaches. Radiative forcing is the change in the balance between radiation coming into the atmosphere and radiation going out. Note that *TA3* impacts only the temperature-related effects of higher atmospheric GHG levels as defined in Part II.D, while *TA2a* and *TA2b* impact both temperature and nontemperature-related effects. It is also important to note that removing GHGs that are already in the atmosphere (*TA2b*) can satisfy the requirements of the Kyoto Protocol, but changing Earth's radiation balance (*TA3*) cannot.[16] The Kyoto Protocol also does not give full credit for the substitution of nuclear for fossil fuel power sources, which are nevertheless included in group *TA2a* to simplify the analysis.

Engineered climate selection has often been referred to as geoengineering, which has been defined by David Keith as "intentional large-scale manipulation of the environment."[17] There are a number of grey areas that fall between decarbonization and geoengineering, but where in doubt they will be assumed to constitute geoengineering for the purposes of this Article.

3. Remedies To Be Extensively Evaluated

In the interests of simplifying the analysis to manageable proportions, the two approaches towards control—management and technologial—will be consolidated for the purposes of this Article into consideration of more limited general types of remedies, which will be extensively analyzed. Since *MA1* has a technological counterpart, which is not to apply technology, and *MA3* also has a technological counterpart (*TA2b* and *TA3*), the choices of remedies *R1* and *R3* are easy. *R2* and *R2a*, however, are more complicated. To simplify the analysis, this delineation omits the following management suboptions: *MA1a, MA2b, MA2c*, and *MA4*. Fortunately, these appear to be closely related in their characteristics to the options that are considered, so will be briefly analyzed in Part V.E after the analysis of the

[16] Kyoto Protocol, *supra* note 1, art. 3, para. 3.

[17] David W. Keith, *Geoengineerig the Climate: History and Prospect*, 25 ANN. REV. ENERGY & ENV'T 245, 247 (2000), *available at* http://www.ucalgary.ca/~keith/papers/26.Keith.2000.GeoengineeringHistoryandProspect.e.pdf.

other options. This leaves the following remedies for the main analysis:

- (*R1*) Nonstabilized "business-as-usual" carbonization and adaptation, based on *MA1*;
- (*R2*) Regulatory decarbonization using "conventional" technologies (*TA1a*) under the Kyoto Protocol (*MA2a*);
- (*R2a*) Nonconventional decarbonization or sequestration (*TA1b*), which could be undertaken under either *MA2* or *MA3*, depending on how *MA2* is implemented;
- (*R3*) Engineered climate selection, combining *MA3* and *TA3*.

Remedies *R2a* and *R3* are broken down into subremedies, primarily along technological lines, since different technologies have different characteristics.

The primary comparison of these remedies can be found in Table 2, which uses the criteria (Columns in Table 2) outlined in Part I.A as the basis for the comparison of the remedies (Rows in Table 2) discussed in Part IV. Figure 1 presents the economic benefit and cost aspects of results shown in Table 2, except that the tools or remedies are shown as vertical columns. This Article relies on a number of previous surveys and reviews in discussing remedies.[18]

This Article considers how each of the four specific problems identified earlier in this Part could be most effectively and efficiently addressed after reviewing a range of alternative solutions that have been proposed for the climate change control problem. The Article

[18] *See* Martin I. Hoffert et al., *Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet*, 298 SCIENCE 981 (2002) (providing a broad overview of the conventional and some of the nonconventional options available, with emphasis on energy production options). There are extensive review articles on both the rationale for using nonconventional approaches as remedies for climate change, *see e.g.*, Jay Michaelson, *Geoengineering: A Climate Change Manhattan Project*, 17 STAN. ENVTL. L.J. 73, 76 (1998) (arguing that "the time has now come to expand our policy horizons to include geoengineering"), and on the approaches themselves, *see* Keith, *supra* note 17, at 259-69 (reviewing various proposals to "geoengineer the climate"). An earlier discussion of some of these remedies can be found in a 1992 National Academy of Sciences report. NAT'L ACAD. OF SCIS., PANEL ON POLICY IMPLICATIONS OF GREENHOUSE WARMING, POLICY IMPLICATIONS OF GREENHOUSE WARMING 433-60 (1992). Judge Posner provides a legal and economic perspective on some of the alternatives. RICHARD A. POSNER, CATASTROPHE: RISK AND RESPONSE (2004). Recent summaries of selected nonconventional options can be found in Tyndall Centre & Cambridge-MIT Institute Symposium, *Macro-Engineering Options for Climate Change Management and Mitigation* (Jan. 7-9, 2004), http://www.tyndall.ac.uk/events/past_events/cmi.shtml [hereinafter Tyndall]. To the extent possible, the options are evaluated using peer-reviewed literature. Where this is not available, the proponents' statements are used as the basis for comparisons, but with the source noted.

begins by briefly summarizing some of the relevant science (Part II) and analyzing the prospects for the Kyoto approach (Part III). The primary discussion of alternative climate change remedies is found in Parts IV and V. The general conclusions with regard to available alternatives are in Part V.D, the application to other management tools in Part V.E, and the application to the four specific problems in Part V.F. The implications of the analysis for the choice of remedies are discussed in Part V.G. Part VI discusses some of the likely major objections to the use of engineered climate selection, and Part VII presents a summary of the Article.

II. CLIMATE CHANGE: THE SCIENTIFIC BACKGROUND

Although the purpose of this Article is not to survey the scientific literature on climate change, a brief discussion of some aspects provides useful background for the remainder of the Article. The emphasis in this Part is on the major causes and effects of global climate change—both anthropogenic and natural.

A. *"Recent" Earth Climate History*

Much of the extensive discussion in recent years of global warming and what, if anything, needs to be done about it, seems to have been largely carried out as if the only alternative to global warming is the climate that prevailed in the late nineteenth or early twentieth century or, at most, that which prevailed over the last twelve thousand years or so of the current interglacial or Holocene Epoch. This appears to ignore the larger reality that Earth has been gripped in a series of extended and worsening ice ages for the last 2.7 million years, so that the "norm" is not the gentle climate of the current Holocene years but rather the predominantly horrific climate of the last three million years since the present series of ice ages began (broken only by relatively short interglacial periods). Interglacial periods have accounted for less than ten percent of the past 900,000 years[19] and represent one extreme of this longer period—the warm extreme. And if the current Holocene interglacial period had followed the pattern of the last several, it would now be ending, in the view of William Ruddiman, with possibly disastrous consequences for further human development.[20] In addition, there is evidence of a Holocene era 1500-

[19] WILLIAM F. RUDDIMAN, PLOWS, PLAGUES, AND PETROLEUM 43 (2005).
[20] *Id.* at 95-105.

year periodicity in Northern Hemisphere temperatures, with the last minimum occurring 400-500 years ago.[21] During the previous interglacial period, there were several such "cold snaps" over intervals of a few decades without significant climatological precursors or warnings.[22] So if "recent" history were the only guide, there is reason to be concerned that the current interglacial period may be near its end and Earth could be headed for another 100,000 years or so in the ice box, or that a new "cold snap" could occur during the current century.[23] Since at least the first of these possibilities would seem to have much greater consequences than global warming, this Article examines the climate change question from a larger perspective of preserving as human friendly a climate as possible rather than the more limited (but still important) objective of avoiding the global warming that now appears to be occurring.

B. *Explanations for Ice Ages*

A number of hypotheses have been proposed to explain these periodic ice ages. The most widely accepted of these is the Milankovitch cycles, but others have suggested variations in the levels of cosmic dust entering Earth's atmosphere, and in solar output.[24] A particularly comprehensive attempt to explain variations in global temperatures based on the Milankovitch cycles and human impacts can be found in *Ploughs, Plagues and Petroleum*.[25]

The important point is that basic causation has not been firmly established, or at least not universally accepted, and is the subject of continuing debate. It is therefore important that any remedies pro-

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[21] Edward Teller et al., *Global Warming and Ice Ages: I. Prospects for Physics-Based Modulation of Global Change* 17 (Univ. of Cal. Lawrence Livermore Nat'l Lab., Working Paper, 1997), *available at* http://www.llnl.gov/global-warm/231636.pdf [hereinafter Teller et al., *Global Warming and Ice Ages*].

[22] *Id.*

[23] *Id.*

[24] See Charles Breiterman, *Considering the Earth as an Open System*, 1 J. EARTH SYS. SCI. EDUC. (2004), http://jesse.usra.edu/articles/breiterman/breiterman-paper.html for a recent survey of this literature. A very recent study suggests that there is a correlation between solar sunspot activity and global temperatures prior to 1970, and that the sun may be going into a quiescent period in which global temperatures could fall by 0.2°C. *See* Stuart Clark, *Saved by the Sun*, NEW SCIENTIST, Sept. 16, 2006, at 32, http://www.newscientist.com/article.ns?id=mg19125691.100&print=true.

[25] *See* RUDDIMAN, *supra* note 19, at 35-168 (arguing that while Earth's climate was determined largely by the Milankovitch cycles prior to 8,000 years ago, man has increasingly assumed indirect control since then).

posed take this uncertainty into account—hence the importance of a criterion allowing for flexible responses (see criterion 5 in Part I.A above).

C. *Long Response Times for Climate System and Influence of Carbon Dioxide and Earth's Radiation Balance on Climate*

Response times are an important aspect of Earth's climate system and vary widely. The system responds very rapidly in terms of changes in ice-cover on land but very slowly in the case of the deep ocean. Because of the slow response times of many of the earth's climate systems, there are long lags in the response of temperatures to changes in GHG emissions and concentrations.[26] Any attempt to actively control climate change needs to take these long response components into account.

It is likely that changes in CO_2 levels in the atmosphere, for example, are important influences on global climate but have a fairly long lead time in human terms.[27] Although not the most potent GHG, CO_2 is the one that many scientists are most concerned about. However, direct attempts to change the incoming radiation from the sun or the outgoing radiation reflected back into space appear to be a more immediate means to influence global temperatures than changing CO_2 levels.

D. *A Very Brief Overview of the Causes and Effects of Global Warming*

The generally accepted theory of global warming is that global temperatures depend on the concentrations of GHGs in the atmosphere, since these change the earth's absorption and retention of heat from the sun. The GHG concentrations, in turn, are determined by the emission of these gases into the atmosphere minus their removal from the atmosphere. The effects of higher GHG concentrations can be broken down into two major categories for the purposes of this analysis, which correspond to problems *P1* and *P2* delineated in Part I.B:

- (*P1*) Those that are a direct result of higher global temperatures;

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[26] *Id.*

[27] *Id.* at 20-21 (comparing the amount of CO_2 in the atomosphere to water in a leaky bathtub, gradually cooling the earth as more and more leaks out).

- (*P2*) Those that are the result of nontemperature effects of higher GHG concentrations in the atmosphere.

E. *Why Accidental Global Warming May No Longer Be Good*

Ruddiman's research implies that Earth and its human cargo had a very narrow escape from the start of a new ice age, and entirely by luck and by human activity undertaken for other reasons, happened to escape what would have been an early end to modern civilization in the northern latitudes.[28] Under this interpretation, human-induced global warming may have saved the day by avoiding a truly catastrophic new ice age, rather than being the cause of the problem.[29] But do we really want to run such risks in the future? Although it appears unlikely that a new ice age would start at current or foreseeable CO_2 levels, it is important to ask: what if Ruddiman is wrong and a new ice age is only a few decades away if there is no intentional human intervention?

F. *Instability, Lack of Full Understanding of Earth's Climate, and the Effects of Short-Term and Unexpected Events*

Substantial uncertainties exist in predicting climate changes. There can be little doubt, based on the results of ice cores retrieved from Greenland and Antarctica, that there have been substantial and sometimes abrupt (as in a decade) climate variations in the past that cannot be explained by the Milankovitch cycles. The result, scientists now believe, is that ice ages can begin or end in as little as a few decades or even a few years.[30]

There is also considerable debate about whether there may be adverse feedback (or triggering of "tipping points," where a slight rise in the earth's temperature can cause a dramatic change in the environment that triggers a far greater increase in global temperatures) from global warming such that further warming would either accelerate global warming, or, working in reverse, bring about an abrupt climate cooling (defined as problem *P3* in Part I.B). Hans Joachim

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[28] *Id.* at 95-105.

[29] *Id.*

[30] *See* RICHARD B. ALLEY, THE TWO-MILE TIME MACHINE: ICE CORES, ABRUPT CLIMATE CHANGE, AND OUR FUTURE 4-5 (2000) (describing the variance in onset times for past ice ages as ranging from less than a decade to more than 10,000 years).

Schellnhuber,[31] James Lovelock,[32] and others have offered a number of concerns about this, including the following:

(1) Thawing of Arctic permafrost may release methane, a potent GHG, which would promote further warming.[33]

(2) Arctic thawing may release sufficient fresh water so as to reduce or even eliminate the oceanic "conveyor belt" that brings warm water into the North Atlantic, warming Europe and North America, and carries away cold, salty water into the South Atlantic and beyond. This could lead to a shift of the tropical rainfall belts.[34]

(3) Disintegration of the Greenland or West Antarctic ice sheets may result in a substantial rise in sea level, and, in the case of Greenland, a reduction in the conveyor belt.[35]

(4) Loss of sea ice in the Arctic Sea may result in increased absorption of sunlight and possibly change major weather patterns.[36] Similarly, a decrease in land coverage of ice and snow would also increase the absorption of sunlight.[37]

(5) As the oceans warm, the ocean area covered by nutrient-poor water may increase and algae growth decrease. This is likely to reduce

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[31] *See* AVOIDING DANGEROUS CLIMATE CHANGE (Hans Joachim Schellnhuber ed., 2006), *available at* http://www.defra.gov.uk/environment/climatechange/internat/pdf/avoid-dangercc.pdf (focusing on the large ice sheets in Greenland and Antarctica and the ocean's thermonaline circulation as the main causes of abrupt climate changes).

[32] *See* JAMES LOVELOCK, THE REVENGE OF GAIA: EARTH'S CLIMATE IN CRISIS AND THE FATE OF HUMANITY 34-35 (2006) (arguing that the systems affecting the Earth's climate reinforce one another).

[33] *See* Fred Pearce, *Climate Warning as Siberia Melts*, NEW SCIENTIST, Aug. 13, 2005, at 12; K.M. Walter et al., *Methane Bubbling from Siberian Thaw Lakes as a Positive Feedback to Climate Warming*, 443 NATURE 71, 71 (2006) (using new methods of measuring ebullition to show that melting permafrost has increased methane release in the Siberian thaw lakes at much higher rates than previously believed); Sergey A. Zimov, Edward A. G. Schuur, & F. Stuart Chapin III, *Permafrost and the Global Carbon Budget*, 312 SCIENCE 1612, 1612-13 (2006) (describing the impact of permafrost melting on atmospheric carbon content).

[34] *See* Laurent Augustin et al., *Eight Glacial Cycles from an Atlantic Ice Cove*, 429 NATURE 623, 626-27 (2004) (describing the effect Arctic thawing has on water temperature in the North and South Atlantic).

[35] *See* Jonathan T. Overpeck et al., *Paleoclimatic Evidence for Future Ice-Sheet Instability and Rapid Sea-Level Rise*, 311 SCIENCE 1747, 1747 (2006) (linking melting ice sheets to rising sea levels).

[36] *See* Gabrielle Walker, *The Tipping Point of the Iceberg*, 441 NATURE, 802, 802 (2006) (discussing the process through which sunlight melts Arctic ice, which creates more open water absorbing more sunlight, thus making warmer summers).

[37] LOVELOCK, *supra* note 32, at 34.

the absorption of CO_2 by the algae and the generation of marine stratus clouds that reflect sunlight.[38]

(6) Increasing global temperatures may destabilize tropical rain forests and lessen the area they cover and the global cooling they provide.[39]

(7) The dark, heat absorbing, boreal forests of Siberia and Canada are likely to extend their range as global temperatures increase.[40]

Whether any or all of these adverse feedbacks exist or not is subject to varying degrees of scientific conjecture, as is whether or when they may result in "tipping points." Presumably these risks should be carefully weighed in any assessment of the risks from problem *P3*. But if any of them appear imminent, humans would be better off taking practical steps to try to avoid them rather than to hope for a miracle. In other words, there is sufficient uncertainty concerning whether and when these events will happen such that it is beneficial to be prepared to move decisively to avert pending problems if they should arise (assuming that nothing is done to prevent them in the first place).

Perhaps the scariest of these risks is (1), methane releases from melting permafrost. A recent article describes the problem in graphic terms as follows:

> The soils of the Arctic are crammed with organic matter—a frozen reservoir of beautifully preserved roots, leaves and other raw material that may contain as much carbon as the whole atmosphere. They are quite unlike soils from more temperate regions, which are mostly made up of the parts that the bacteria cannot digest. "We are unplugging the refrigerator in the far north," says [Phil] Camill [of Carleton College]. "Everything that is preserved there is going to start to rot."
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> Although such feedback has been discussed for almost as long as the threat of global warming has been taken seriously by scientists, the lack of firm data on the subject is striking. "There is a lot that we don't know at this point," says Walter Oechel from San Diego State University in California. "People haven't quite pulled the whole picture together yet—but what we do know is that the potential amounts are huge and very, very scary."[41]

One of the most widely publicized of these risks is (2). Some scientists have proposed that some of the past abrupt climate changes

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[38] *Id.*

[39] *Id.*

[40] *Id.*

[41] Gabrielle Walker, *A World Melting from the Top Down*, 446 NATURE 718, 718-21 (2007).

were caused by a breakdown of the oceanic "conveyor belt" that brings warm water into the North Atlantic, warming Europe and Eastern North America, and carries away cold salty water to the South Atlantic and beyond.[42] There are recent indications that the "conveyor belt" has weakened by about thirty percent in recent years, possibly because of an influx of less saline water into the North Atlantic as a result of global warming-induced thawing in the Arctic.[43] The conveyor belt is believed to have broken down in the past. Some scientists believe that this happened during the Younger Dryas cooling about 12,600 years ago.[44] This event began suddenly, and for its 1000-year duration the North Atlantic region was about 5°C colder.[45] Although this is not deemed an ice age in itself, it may have felt like one to the generations who lived through it and would certainly have large economic effects on Western Europe and possibly elsewhere if it should recur today. One recent study concluded that there is a fifty percent risk of such a conveyor belt collapse absent any action to prevent global warming.[46] But even with the addition of a carbon tax as might occur under *MA2*, the study found that there would still be a twenty-five percent risk which *MA2* would not address even if it were fully implemented. The authors' conclusions would seem to have a direct bearing on the questions posed in this Article:

> Such high probabilities are worrisome. Of course they should be checked by additional modelling studies. But, if these future studies find similar results, it would seem that the risk of a THC [conveyor belt] collapse is unacceptably large and, therefore, that measures over and above the policy intervention of a carbon tax be given serious consideration.[47]

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[42] *See, e.g.*, Wallace S. Broecker, *Thermohaline Circulation, the Achilles Heel of Our Climate System: Will Man-Made CO_2 Upset the Current Balance?*, 278 SCIENCE 1582, 1582-84 (1997) (describing the "conveyor belt" system).

[43] *See* Harry L. Bryden, Hannah R. Longworth & Stuart A. Cunningham, *Slowing of the Atlantic Meridional Overturning Circulation at 25° N*, 438 NATURE 655, 655-57 (2005) (listing evidence that "suggests that the Atlantic meridional overturning circulation has slowed by about 30 per cent between 1957 and 2004").

[44] Michael E. Schlesinger et al., *Assessing the Risk of a Collapse of the Atlantic Thermohaline Circulation* (Feb. 1, 2005), *available at* http://www.stabilisation2005.com/Schlesingerm_Thermohaline.pdf.

[45] Terrence M. Joyce, Presentation to the U.S. Commission on Ocean Policy: *Abrupt Climate Change and the Oceans*, 1 (Sept. 24-25, 2002), *available at* http://www.oceancommission.gov/meetings/sep24_25_02/joyce_testimony.pdf.

[46] Schlesinger, *supra* note 44, at 1.

[47] *Id.* at 6-7.

Although the modeling results of this particular study may or may not be supported by future studies, and there is doubt among some scientists that global warming could bring about a new collapse of the conveyor belt, some scientists warn that global warming could result in other abrupt and serious regional climate changes.[48]

Despite considerable research to build better climate models, it is safe to say that considerable uncertainties remain. One illustration of this is the debate over global dimming, and the extent to which increased pollution in the twentieth century may have masked the impact of higher CO_2 levels on global temperatures.[49] It is even conceivable (although probably unlikely) that, if pollution should substantially decrease (as might be the case if a successful effort were actually made to decrease CO_2 emissions), the result could be an unexpected plateau or even an increase in global temperatures as the dimming effect diminishes at the same time that GHG emissions decrease. Given the lag between changes in emissions and changes in atmospheric concentrations of CO_2, in fact, this could conceivably happen in the early years of an effective effort to decrease global CO_2 emissions.

G. *Volcanic Eruptions and Nuclear Conflicts as a Cause of Climate Cooling (Problem* P4*)*

One known source of shorter-term climate cooling that is widely ignored in discussions of climate change is major volcanic eruptions that place sulfur-containing gases into the stratosphere. As a result of observations concerning the climatic effects of major volcanic eruptions such as El Chichon and Mount Pinatubo, which resulted in significant observed global cooling, it has been clear that sulfur-containing gases that reach the stratosphere from major eruptions cool the planet,[50] although they are clearly dirty and involve grossly

[48] *See* Richard A. Kerr, *Confronting the Bogeyman of the Climate System,* 310 SCIENCE 432, 433 (2005) (surveying possible climate threats greater than a collapse of the conveyor belt).

[49] Gerald Stanhill & Shabtai Cohen, *Global Dimming: A Review of the Evidence for a Widespread and Significant Reduction in Global Radiation with Discussion of Its Probable Causes and Possible Agricultural Consequences*, 107 AGRIC. & FOREST METEOROLOGY 255 (2001) (discussing the causes and consequences of global dimming).

[50] *See* Alan Robock, *Volcanic Eruptions, in* ENCYCLOPEDIA OF GLOBAL ENVIRONMENTAL CHANGE 738, 738-44 (Ted Munn ed., 2002), *available at* http://climate.envsci.rutgers.edu/pdf/EGECVolcanicEruptions.pdf (describing the cooling impact of volcanic dust); Shanaka L. de Silva, *Volcanic Eruptions and Their Impact on the*

"oversized" aerosols lifted to a less than "optimal" altitude if the purpose were to decrease global temperatures. Sulfur combines with water vapor in the stratosphere to form dense clouds of tiny droplets of sulfuric acid. These decrease tropospheric temperatures because they absorb incoming solar radiation and scatter it back into space.

The severity of the climatic effect depends on the magnitude of the eruption, the sulfur content of the magma, and the amount of sulfur released into the stratosphere as an aerosol.[51] For extremely large eruptions, the climatic effects will persist until the sulfur compounds gradually drop to lower altitudes where they are washed out by rain. In the case of major eruptions such as Mount Tambora in 1815, the climatic effects were observed in 1816, the "year without a summer."[52]

Volcanic eruptions come in many shapes and sizes. The most devastating of them are characterized as supervolanic eruptions. The effects of these can be disastrous in terms of the area buried by ash, the effects on the environment, and the resulting decrease in temperatures as a result of stratospheric scattering of incoming sunlight. One study suggested that the Toba eruption in what is now Indonesia, occuring roughly 74,000 years ago, might have created 5,000 tons of sulphuric acid aerosols in the atmosphere.[53] The authors concluded that this may have resulted in global temperatures falling by 3° to 5°C. They further suggested that the eruption may have accelerated the world into the last ice age, from which it only emerged about 10,000 years ago. Other researchers have found evidence of an abrupt five- to six-year decrease in temperatures close to the time of the eruption.[54] Based on all this an anthropologist has proposed that the Toba eruption may have been responsible for a human population "bottleneck" about that time in which only a few thousand survived.[55] Other researchers are less certain.[56] A calculation by still other researchers

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Earth's Climate, *in* ENCYCLOPAEDIA OF WORLD CLIMATE 788, 788-94 (J. Oliver ed., 2002), *available at* http://www.space.edu/documents/Volcanoclimate.pdf.

[51] De Silva, *supra* note 50.

[52] *Id.*

[53] Michael R. Rampino & Stephen Self, *Volcanic Winter and Accelerated Glaciation Following the Toba Super-Eruption*, 359 NATURE 50-52 (1992).

[54] G.A. Zielinski et al., *Potential Atmospheric Impact of the Toba Mega-Eruption*, 23 GEOPHYSICAL RES. LETTERS 837, 837-40 (1996).

[55] Stanley H. Ambrose, *Late Pleistocene Human Population Bottlenecks, Volcanic Winter, and Differentiation of Modern Humans*, 34 J. HUM. EVOLUTION, 623, 623-51 (1998).

[56] Clive Oppenheimer, *Limited Global Change Due to the Largest Known Quaternary Eruption*, 21 QUATERNARY SCI. REV. 1593-1609 (2002).

has been made that there is a one percent chance of a super-eruption in the next 460 to 7,200 years.[57]

A very similar situation exists with regard to potential asteroid impacts[58] and nuclear conflicts,[59] which can also result in global temperature decreases. Ben Mason et al. calculated that such volcanic eruptions are considerably more frequent than asteroid impacts of similar energy yield.[60] Even regional nuclear conflicts would likely generate very large amounts of soot that would reach the stratosphere as a result of fires caused by nuclear explosions.[61] Although the Toba eruption occurred before humans kept accurate climate or popuation records, it would appear that some such short-term volcanic events may have a greater impact on human welfare than those resulting from current global warming or asteroid impacts. Although some effort is being proposed to reduce global warming and some effort is already being made to predict asteroid impacts, it appears that nothing is being done to reduce the climatic effects of large volcanic eruptions.

Unlike global warming, adaptation is very difficult in the case of major eruptions or nuclear conflicts since their timing and the magnitude of their effects are currently unpredictable. There can be little doubt that there will be future major volcanic eruptions that will affect climate. There were approximately ten in the twentieth century, or an average of one per decade.[62] None of these ten was catastrophic in terms of its effects. De Silva states that it is generally accepted that there will be an average temperature decrease of 0.2° to 0.5°C for one

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[57] Ben G. Mason, David M. Pyle & Clive Oppenheimer, *The Size and Frequency of the Largest Explosive Eruptions on Earth*, 66 BULL. OF VOLCANOLOGY 735, 735-48 (2004).

[58] T. Luder, W. Benz & T.F. Stocker, *Modeling Long-Term Climatic Effects of Impacts: First Results*, *in Catastropic Events and Mass Extinctions: Impacts and Beyond*, GEOLOGICAL SOC. OF AM. 717-29 (Special Paper 356, C. Kocherl & K.G. McLeod eds., 2002); *available at* http://www.climate.unibe.ch/~stocker/papers/luder02gsa.pdf (noting that temperature drops and darkness lasting many months are some of the outcomes triggered by impact of asteroids and comets on the earth).

[59] *See* Alan Robock et al., *Climatic Consequences of Regional Nuclear Conflicts,* 6 ATMOSPHERIC CHEMISTRY & PHYSICS DISCUSSION 11,817, 11,818 (2006), *available at* http://climate.envsci.rutgers.edu/pdf/acpd-6-11817.pdf (predicting famine for billions as a result of a nuclear winter that would follow the massive use of nuclear weapons).

[60] Mason et al., *supra* note 57.

[61] Robock et al., *supra* note 59.

[62] *See* David Viner & Phil Jones, *Volcanoes and Their Effect on Climate* (Climatic Res. Unit, Sch. of Envtl. Scis., U.E. Anglia) (2000), *available at* http://www.cru.uea.ac.uk/cru/info/volcano.

to three years after a major eruption, although there is great variability between eruptions based on the factors mentioned in the preceding paragraph.[63] This compares with an increase of global temperatures of about 0.6°C during the twentieth century. Although no estimate of the economic damages from such decreases is available, there are very likely to have been substantial costs, perhaps even as much as the costs of global warming to date, given the greater difficulty of adapting to these effects. It is also highly probable, if not certain, that one or more future volcanic eruptions will at some time be a supervolcanic eruption.[64] Many scientists believe that such a supervolcanic eruption can be expected in Yellowstone National Park as well as elsewhere.[65] Such eruptions have occurred about 600,000 to 700,000 years apart near Yellowstone, and it has been 640,000 years since the last one. When it occurs, it is expected to have catastrophic results for both the United States and the world. There is no known way to decrease the direct effects of such an eruption, such as pyroclastic flows and nationwide ash falls, but it would appear possible to prevent or reduce the indirect effects on global temperatures if immediate action could be taken to increase global temperatures when such eruptions occur. These indirect effects on global temperatures, sometimes described as a volcanic winter, would probably decimate agricultural production and thus human food supplies, something that the survivors would desperately need. It should be noted that the question appears to be not whether there will be future eruptions that will affect climate, but rather when and where they will next occur and how serious the effects will be. The risks of such adverse events are somewhat different from those of the other three problems listed in Part I.B. There is a virtual certainty of short-term impacts averaging 0.2° to 0.5°C once a decade or so and a risk of extremely catastrophic events with a much longer and even more uncertain time interval. There appear to have been few if any attempts to reduce these risks from volcanic eruptions.

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[63] *See* de Silva, *supra* note 50.

[64] A super-volcano is defined as one that has a volcanic explosivity index (VEI) of 8. *See* Bill McGuire, *How To Measure the Size of a Volcanic Eruption*, GUARDIAN (London), Sept. 2, 2004, at 9.

[65] Ilya N. Bindeman, *The Secrets of Supervolcanoes*, SCI. AM., May 22, 2006, at 36, 38, 40 *available at* http://www.scientificamerican.com/print_version.cfm?articleID=0006E0BF-BB43-146C-BB4383414B7F0000.

H. *What Might the Future Hold?*

What can we conclude from this brief overview of climate change science? Global temperatures appear to be affected by both human activities as well as short- and long-term natural events and forces. This makes predictions of future temperatures risky, although it is clear that they need to be viewed from both a much shorter and a much longer time horizon than that of the current warming period. Ruddiman provides an extensive discussion of some of the possibilities.[66] He agrees that warming is the principal threat in the next few centuries, but that an ice age is a longer-term possibility. A recent study with a longer than usual time horizon concludes that a "business-as-usual" approach to the use of fossil fuels is likely to lead to an 8.05° C (14.5°F) rise in average global temperatures by the year 2300.[67] It appears likely that the global warming that occurs will be interrupted every decade or so (on average) by unpredictable one- to three-year global cooling from major volcanic eruptions, and although much less likely, it is even possible that there will at some point in the future be a volcanic or nuclear winter (as a result of a supervolcanic eruption or a nuclear conflict) or other abrupt climatic change resulting in serious global cooling. There may also be "tipping points," where a continued rise in global temperatures will trigger very adverse environmental effects. It would therefore appear prudent for humans to consider how best to counter continuing global warming while at the same time developing the capability to counter shorter-term global cooling or warming on a rapid response basis.

III. WHY THE KYOTO PROTOCOL WILL NOT PREVENT CLIMATE CHANGE AND IS UNLIKELY TO ACHIEVE ITS GOALS

The most prominent current management tool to control global climate change is represented by the Kyoto Protocol, which seeks to limit emissions of GHGs by the wealthier nations. The next objective of this Article is to analyze the Protocol to see if it is likely to prevent adverse climate change or to achieve the goals set for it. Most economists who have examined it have seen it as deeply flawed.[68] But before

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[66] *See* RUDDIMAN, *supra* note 19, at 171-74.

[67] *See* G. Bala et al., *Multicentury Changes to the Global Climate and Carbon Cycle: Results from a Coupled Climate and Carbon Cycle Model*, 18 J. CLIMATE 4531, 4532-33 (Nov. 2005).

[68] Sheila M. Olmstead & Robert N. Stavins, *An International Policy Architecture for the Post-Kyoto Era*, 96 AM. ECON. REV. PAPERS & PROC. 35, 35 (2006).

examining the Protocol, it is important to define what the phrases "Kyoto approach" and "prevent global warming" mean as used in this Article.

A. *What Is Meant by the Kyoto Protocol and Approach?*

The "Kyoto Protocol" as used in this Article includes any control measure explicitly sanctioned by the Kyoto Protocol and its approved implementing instruments. The "Kyoto approach" includes both those actions specifically called for by the Protocol as well as other regulatory decarbonization proposals that would have the same effect and use the same general means. Examples of other measures include the recent law enacted in California requiring drastic reductions in GHGs emitted in the state,[69] and bills that have been introduced into the U.S. House and Senate to do roughly the same thing nationally.[70] Although Part III deals primarily with the Protocol, many of the conclusions reached also apply to other proposals that would fall under the Kyoto approach. These other proposals are dealt with more explicitly in Part V.E.

B. *UN/EU Goals for Controlling Global Warming*

The common understanding of the phrase "prevent global warming" is presumably that global temperatures would not be allowed to rise beyond what they currently are. This is not, however, the definition used in the discussion of the United Nations Framework Convention on Climate Change (UNFCCC). Its much less demanding definition is that there be "stabilization of greenhouse gas concentrations . . . at a level that would prevent dangerous anthropogenic interference with the climate system."[71]

The UNFCCC definition of "dangerous anthropogenic interference" is a very slippery one since the effects on global temperatures depend on when the levels are stabilized and the GHG concentrations they are stabilized at, which in turn depends on what level is needed to "prevent dangerous anthropogenic interference with the climate system." In other words, this definition does not prevent global warm-

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[69] *See* California Global Warming Solutions Act of 2006, CAL. HEALTH & SAFETY CODE § 38500 (West 2007).

[70] *See, e.g.*, H.R. 5642, 109th Cong. (2006); S. 3698, 109th Cong. (2006).

[71] UN Framework Convention on Climate Change art. 2, May 9, 1992, 1771, *available at* http://unfccc.int/resource/docs/convkp/conveng.pdf.

ing in the common understanding of the phrase. Rather, it says that atmospheric GHG levels should be stabilized at a level that is not "dangerous." The European Union has a target of restricting global warming to 2°C above preindustrial levels, presumably because it believes that any temperature rise above that amount would be "dangerous."[72] Most of the major proposals to limit GHG emissions use this as their goal, so it will be used in this Article as the basis for judging the effectiveness of the global warming aspects of the management approaches analyzed. Two bills introduced in the U.S. Congress in 2006 specify a similar goal of average temperature rises of no more than 2°C and stabilization of CO_2 levels at 450 ppm.[73]

One obvious question is whether a reasonable solution to the global warming problem would be to change the interpretation of the goal so that warming above 2°C would be acceptable. This is a very important question, but it is outside the scope of this Article, since the Article assumes that the goal for global warming control is that which is specified by the proponents of GHG control. There are several points that need to be made concerning this assumption, however.

The first point is that *P3*, the risk of abrupt climate changes resulting from higher average world temperatures, presumably increases as temperatures rise. So, although there is no certainty that all abrupt changes can be avoided if temperature changes are kept below 2°C, there is believed to be a rapidly increasing risk above that level and no certainty that 2°C is entirely safe either. Possibly for this reason, the 2°C limit has become the "standard" by which the effectiveness of climate change control strategies are usually judged, and it is the basis for most proposals to reduce global warming, as well as the one used in this Article.

The second point is that reasonable variations on the 2°C limit would not change the major conclusions of this Article. If the limit

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[72] Council of the European Union, Climate Change: Medium and Longer Term Emission Reduction Strategies, Including Targets—Council Conclusions, Brussels, March 11, 2005, *available at* http://register.consilium.europa.eu/pdf/en/05/st07/st07242.en05.pdf. According to George Monbiot, the aim of preventing more than 2°C warming has also been overtly adopted by the UN and implicitly by the British, German, and Swedish Governments. He also describes his rationale for the target. *See* George Monbiot, *Giving Up on Two Degrees*, May 1, 2007, *available at* http://www.monbiot.com/archives/2007/05/01/1058. The article is also available as George Monbiot, *The Rich World's Policy on Greenhouse Gas Now Seems Clear: Millions Will Die,* GUARDIAN UNLIMITED (London), May 1, 2007, *available at* http://www.guardian.co.uk/commentisfree/story/0,,2069395,00.html.

[73] *See* H.R. 5642 § 702; S. 3698, § 701.

were 3°C or even 4° or 5°, engineered climate selection would still be the lowest cost means for meeting the higher limit since the cost is roughly 1/4000 as much as for meeting the 2°C limit using Remedy *2*. So, although it is not clear what the cost might be for higher limits, it is clear that it is not three or four orders of magnitude less. If, on the other hand, there is no temperature change that would result in significantly increased risk of abrupt climate changes, there is no need for any climate change control to reduce *P3*.

The third point is that hopefully the risks listed above in Part II.F, as well as others, were carefully weighed by those who set the 2°C limit, although some were probably not even known at the time.

C. *GHG Stabilization Under the Kyoto Protocol*

1. Kyoto Goals Unlikely To Be Met by Most Participating Annex I Countries

The first question to be asked is whether the emission goals specified in the Kyoto Protocol are likely to be met by the participating Annex I countries (i.e., those that ratified the Protocol and are obligated by it to make emission reductions). Currently available information suggests that it is highly unlikely that the reductions specified in the agreement will be fully achieved in most of these countries. In November 2005, the European Environment Agency warned "that the EU was likely to cut its emissions by only 2.5% by the year 2012."[74] In December 2005, the Institute for Public Policy Research concluded that ten of fifteen EU signatories would miss their Kyoto targets without "urgent action."[75] An earlier 2003 European Environment Agency report reached the same conclusion.[76]

Reductions in possible later follow-on periods are likely to prove even more difficult for a number of participating Annex I nations (such as Germany and Russia) because of the fortuitous choice of 1990 as a base year when emissions were high relative to later in the 1990s.

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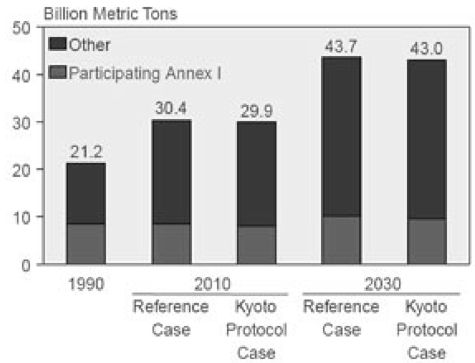
[74] *Europe 'Behind on Kyoto Pledges'*, BBC NEWS, Dec. 26, 2005, http://news.bbc.co.uk/2/hi/uk_news/politics/4561576.stm.

[75] *Id.*

[76] Norm Dixon, *Global Warming: Can Kyoto Accord Really Help?*, BALT. CHRON. & SENTINEL, Feb. 18, 2005, *available at* http://baltimorechronicle.com/021805Dixon.shtml.

Figure 2: World Carbon Dioxide Emissions in Two Cases, 1990, 2010, and 2030[77]



2. If Achieved for Participating Nations, Kyoto Goals Are Not Projected To Stop CO_2 Emission or Temperature Increases

The most recent estimates of future world CO_2 releases, assuming implementation of the Kyoto Protocol in participating Annex I countries and a continuation of it in future possible follow-on agreements, suggest that CO_2 emissions will continue to increase (see Figure 2).[78] Specifically, the U.S. Department of Energy projects that in this case world CO_2 emissions will increase 44% from 2010 to 2030 and 106% from 1990 to 2030 (as compared with a Kyoto proposed decrease of 5.3% from 1990 to 2012).[79] As long as emissions continue to increase, CO_2 concentrations will not fall. Other analyses of atmospheric concentrations of GHGs also indicate that CO_2 would continue to increase,[80] although perhaps at a slower rate than it otherwise would.

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[77] This figure is taken from U.S. DEPT. OF ENERGY, INTERNATIONAL ENERGY OUTLOOK 2006, at fig.6 (2006), *available at* http://www.eia.doe.gov/oiaf/archive/ieo06/highlights.html.

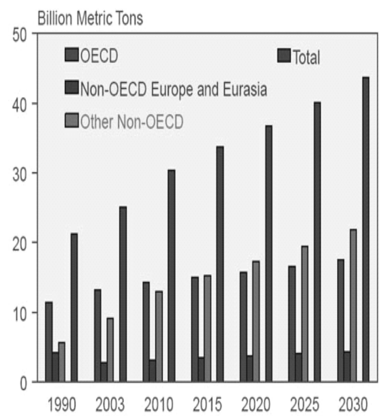
[78] *Id.*

[79] *Id.*

[80] John Bongaarts, *Population Growth and Global Warming*, 18 POPULATION & DEV. REV. 299, 302 (1992); Ken Caldeira, Atul K. Jain & Martin I. Hoffert, *Climate Sensitivity Uncertainty and the Need for Energy Without CO_2 Emission*, 299 SCIENCE 2052, 2052-54 (2003) .

The much more drastic reductions in overall fossil fuel use required for temperature stabilization[81] are highly unlikely, particularly during a period when use by less developed countries is rapidly increasing and is uncontrolled under the Protocol. Any "savings" from decreased developed country use are likely to be more than lost to Asian fossil fuel use increases (see Figure 3).

Figure 3: World Carbon Dioxide Emissions by Region, 1990–2030[82]



The extra annual emissions of CO_2 from new coal-fired plants in China, India, and the United States are expected to exceed the projected reductions from Kyoto by more than a factor of five by 2012.[83]

Current projections of CO_2 releases by the International Energy Agency similarly suggest that the Kyoto targets will not be met on a worldwide basis.[84]

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[81] Bongaarts, *supra* note 80, at 312.

[82] This figure is taken from INTERNATIONAL ENERGY OUTLOOK 2006, *supra* note 77, at fig.65.

[83] For an excellent graph representing these expectations, see Scott Wallace, Sources and industry estimates for *Extra Annual Emissions of CO_2, UDI-Platt's, U.S. Energy Information Administration*, CHRISTIAN SCI. MONITOR, Dec. 23, 2004.

[84] The International Energy Agency's World Energy Outlook (WEO) Reference Scenario projects, based on policies in place, that by 2030, CO_2 emissions will have increased by 63% from today's levels, which is almost 90% higher than 1990 levels. Even in the WEO's 2004 World Alternative Policy Scenario—which analyzes the impact of additional mitigation policies up to 2030—global CO_2 emissions would increase 40% from today's level, putting them 62% higher than in 1990. *See* IEA, Overview: Pros-

One study, presented in early 2005, concluded that GHG emissions would have to fall to between 30% and 50% of 1990 levels by 2050 if there is to be a 50-50 chance of avoiding a temperature increase of more than 2°C.[85] That would mean a 50% to 70% decrease from 1990 levels and an even greater decrease from 2006 levels. Greater assurance than a 50-50 chance of meeting the goal would require even larger reductions. The two bills introduced into the U.S. Congress in 2006 specify a goal of an 80% reduction in CO_2 emissions by 2050 from 1990 levels in order to prevent more than a 2°C rise in temperature above the preindustrial average and global atmospheric concentrations of GHGs (presumably they actually mean CO_2) from exceeding 450 ppm.[86] In other words, the average person in the world would have to decrease his or her direct and indirect GHG-emitting activities by two-thirds or even four-fifths at the same time that the developing countries are trying to rapidly increase their energy use. If, as the developing countries now insist, they continue to very rapidly increase their emissions, the percentage reductions required by the developed world would be still greater. Caldeira and his coauthors conclude that even if climate sensitivity is at the lower end of the range of uncertainty, over 75% of primary power would need to come from non-CO_2 emitting sources if the 2°C goal is be met.[87] And if climate sensitivity is at the higher end of the range of uncertainty, "nearly all of our primary power will have to come from non-CO_2 emitting sources."[88] Put in simpler terms, this would mean that nearly every electric power plant would need to be replaced with a hydro-, wind-, or nuclear-based facility. This strongly suggests that trying to meet the 2°C goal using this approach would be somewhere between extremely difficult and impossible. Reuel Shinnar and Francesco Citro estimate that $170 to $200 billion *per year* would be required to achieve a 70% reduction in U.S. CO_2 emissions over 30 years.[89] Presumably if other countries did not meet similar reductions, the United States would have to achieve much higher percentage reductions if

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pects for CO_2 Capture and Storage (2005), *available at* http://www.iea.org/textbase/npsum/ccsSUM.pdf.

[85] Jenny Hogan, *Only Huge Emissions Cuts Will Curb Climate Change*, NEW SCIENTIST.COM, Feb. 3, 2005, http://www.newscientist.com/channel/earth/climate-change/dn6964. Monbiot, *supra* note 72, says that an 80% cut from current levels would be needed.

[86] *See* H.R. 5642, 109th Cong. (2006); S. 3698, 109th Cong. (2006).

[87] *See* Caldeira et al., *supra* note 80, at 2053.

[88] *Id.* at 2054.

[89] Reuel Shinnar & Francesco Citro, *A Road Map to U.S. Decarbonization*, 313 SCIENCE 1243, 1244 (2006). The total undiscounted cost would be about $6 trillion.

the 2°C goal were to be met. So it is not impossible—just extremely expensive and impractical unless the population is placed on a freedom-of-choice limiting energy rationing system, such as has recently been discussed in Great Britain, and unless the rest of the world (including the developing nations) achieves similar reductions.

The emissions reductions required by the Kyoto Protocol would have a negligible effect on global temperatures. A study by the National Center for Atmospheric Research concluded that the change in global temperatures, even with United States participation, would be a reduction of 0.11° to 0.21°C (about 6%) off global average temperatures by 2100 assuming that the Annex I nations continued to observe the Kyoto limits beyond 2012.[90] If they went back to business as usual after 2012, the reduction would only have been about 3%. The nonparticipation by the United States in Kyoto Protocol would make these effects even lower.

But the Kyoto goals currently only apply to industrialized participating signatories to the Protocol, whereas much of the increase in CO_2 emissions are projected to come from the less developed countries in coming years. "Mature market economies" are projected to increase their CO_2 emissions by 1.0% per year over the period 2002 to 2025;[91] "emerging economies" are projected at 3.2% including China at 4.0%.[92]

The response of those advocating GHG emission control has been to argue that improved technology will come to the rescue.[93] More

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[90] T.M.L. Wigley, *The Kyoto Protocol: CO_2, CH_4 and Climate Implications*, 25 GEOPHYSICAL RES. LETTERS 2285 (1998), summary *available at* http://www.ucar.edu/news/record/#kyoto.

[91] Energy Info. Admin., *Emissions of Greenhouse Gases in the United States 2004*, Report No. DOE/EIA-0573, at tbl.1 (Dec. 2005), *available at* http://www.eia.doe.gov/oiaf/1605/gg05rpt/emission_tbls.html.

[92] *Id.*

[93] Some of the proponents of the Kyoto Protocol approach have recently made quite sophisticated arguments concerning the effects of endogenous technical change on the costs of control, which they believe will bring down the cost of meeting the EU/UNFCCC goal considerably. Jonathan Köhler et al., *The Transition to Endogenous Technical Change in Climate-Economy Models: A Technical Overview to the Innovation Modeling Comparison Project*, ENERGY J. (SPECIAL ISSUE) 2006, at 17, 36-38. Although there would undoubtedly be endogenous technical change, these arguments are questionable on a number of grounds. They assume that much of the relevant technical change will result from "learning by doing" rather than from unrelated developments in other sectors. Experience with the development of motor vehicle hybrids, however, which depend on sophisticated computer technology, among other developments, make such assumptions dubious. They also appear to assume that increased R&D on emissions reduction technology will not have serious adverse effects on other sectors

generally, proponents of Kyoto appear to believe that Kyoto was never intended as the ultimate solution to global warming, but rather as a first step down a path that would ultimately lead to achievement of the UNFCCC goal. Currently, however, there is little evidence that countries not listed in Annex I are making any serious efforts to reduce GHG emissions. Proponents hope that possible follow-ons to Kyoto will involve much greater GHG emission reductions that would make goal achievement possible. Whether there will be follow-ons and if so, whether they would involve more effective reductions, is uncertain at this time. The COP11 meeting in Montreal in late 2005 and the COP12 meeting in Nairobi in late 2006 were not particularly encouraging in this respect since the underlying disagreements between the developed and less developed countries appear to be unchanged.

3. Even If a Program To Implement the EU/UNFCCC Goals Were Somehow Effectively Implemented Worldwide, There Would Still Be a Substantial Risk of Temperature Exceedences and the Need for Adaptation

Worldwide CO_2 emissions are projected to increase at roughly 2% per year in the period 2002 to 2025,[94] which probably implies an increase in atmospheric CO_2 levels of about 2 ppmv per year;[95] atmospheric CO_2 levels were about 380 ppmv in 2006.[96] Taking into account other GHGs besides CO_2 (such as methane), however, CO_2e equivalent levels were at least 420 in 2006.[97] Hare and Meinshausen

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from which scarce R&D resources would be diverted since these costs appear not to have been factored in.

[94] U.S. Department of Energy, Energy Information Administration, *International Energy Outlook 2005* 78 (2005), available at http://tonto.eia.doe.gov/FTPROOT/forecasting/0484(2005).pdf.

[95] Atmospheric levels have been increasing about 2 ppmv per year, *see* Dialing in Your Own Climate, Fig. 2a, http://www.worldclimatereport.com/index.php/2006/04, in very recent years, up from an average annual increase of 1.4 ppmv from 1959 to 2004. *See* C.D. Keeling & T.P. Whorf, *Atmospheric CO_2 Records from Sites in the SIO Air Sampling Network, in* U.S. DEPT. OF ENERGY, TRENDS: A COMPENDIUM OF DATA ON GLOBAL CHANGE. (Carbon Dioxide Info. Analysis Ctr., 2005), available at http://cdiac.ornl.gov/trends/co2/sio-mlo.htm.

[96] *Id.*

[97] Bill Hare and Malte Meinshausen state that there is a 40 ppm difference between CO_2 and CO_2e levels. Bill Hare & Malte Meinshausen, *How Much Warming Are We Committed to and How Much Can Be Avoided?* 75 CLIMATIC CHANGE 111 (2006). The *Stern Review* uses 430, *see supra* note 3, at vii. Other recent estimates of CO_2e range as high as 459. *See* Monbiot, *supra* note 72. Keeling and Whorf report atmospheric concentrations of 377 ppm CO_2 in 2004, Keeling & Whorf, *supra* note 95. At a 2 ppm per year increase, the 2006 level of CO2e would be about 420.

conclude that only with CO_2 levels stabilized below 400 CO_2 (or 440 CO_2e) is there more than a 66% chance of limiting global mean temperature increases to below 2°C.[98] They further state that "Four out of the 7 more recent climate sensitivity … estimates suggest that CO_2eq concentrations have to be even lower in order to have a 'likely' chance of achieving a 2°C target, namely below 400ppm CO_2eq in equilibrium."[99] Put another way, they conclude that "only for stabilization levels of 400 ppm CO_2 equivalent and below, the possibility that warming of more than 2°C will occur could be classified as 'unlikely.'"[100] Since by 2007 we are now at least 20 ppm over 400 CO_2e and 20 ppm or less under 440, it appears safe to conclude that there is a significant risk that the 2°C increase target will be exceeded, and that within 10 years 440 will be exceeded except in the unlikely case that extremely drastic action is taken to bring down future emissions over the next few years. These higher temperatures would presumably result in considerable human adaptation, thus decreasing the economic benefits from imposing emission controls, in addition to the risk of abrupt climate changes (*P3*).

4. Successful Achievement of Goals Is Too Demanding of People and Their Governments

Attempting to control CO_2 and other GHG concentrations to levels that would meet the EU/UNFCCC goals by using the Kyoto approach would require a large measure of international collaboration, development of complex regulatory systems, willingness of governments to ignore their countries' self-interest, and willingness of billions of people to make personal sacrifices. The benefits made possible by CO_2 emissions are basic to modern civilization and provide huge economic incentives for continued increases. Efforts to control CO_2 emissions suffer from the immense costs of shifting modern society away from its increasing dependence on fossil fuels as a source of energy for economic growth and development. Significant progress assumes that people would agree to, and actually implement, greatly decreased fossil fuel consumption, which assumes that people would be willing to give up some of the very real benefits they enjoy from the use of fossil fuels at current or higher levels without a clear-cut, immediate "crisis" to spur them into making such sacrifices. The following quotation from Ruddiman explains some of the problems very

[98] Hare & Meinshausen, *supra* note 97.
[99] *Id.*
[100] *Id.* at 25.

well, from the point of view of someone with as intimate a knowledge of the GHG emissions reductions that would be required as probably anyone:

> [There is] an unspoken truth about global warming that for some reason politicians of both parties ignore. To reduce current and further greenhouse-gas emissions to levels that would avoid *most* of the projected future warming, draconian economic sacrifices would have to be enacted that almost everyone would find intolerable: much more expensive fuel for travel and heating, much lower/higher thermostat settings in houses and workplaces, and extremely costly upgrades (or total replacements) of power plants. The drag on the economy and on quality of life from such efforts would be enormous, and few citizens would stand for it. At this time, with current technologies, we simply cannot afford the effort that would be required to mitigate the main impact of global warming.[101]

This paragraph points out one of the fundamental problems in the current approach to climate change problems adopted by most of the developed world. Almost no one except Ruddiman has tried to explain the magnitude of the problems that would result if GHG emissions were to be reduced sufficiently to avoid both warming and adverse climate feedbacks, or "tipping points." An effective GHG emission control approach is not a matter of maintaining the current lifestyle in the developed world with a few adjustments and the use of more energy-saving technology. Rather, as discussed above in Part III.C.2, it would require wholesale changes in lifestyles in the developed world and radical changes in the development efforts of the less developed world, as well as the introduction of most available technology, probably regardless of how expensive it may prove to be. It is hard to overemphasize the importance of this reality. As Ruddiman says, this is "an unspoken truth."[102]

A more analytical approach might separate the GHG reduction problem into two components:

(1) Those measures that involve achieving roughly the same level of individual welfare and personal freedom of choice, at a lower cost in GHG emissions. The disadvantage of such reductions is that they will usually increase the costs involved, which usually have an indirect effect on living standards as well as on international competitiveness if

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[101] *See* RUDDIMAN, *supra* note 19, at 183.

[102] *Id.*

not undertaken by everyone in the world. Examples include substituting nuclear power for fossil fuel based electric power.[103]

(2) Those measures whose primary effect is to lower individual welfare and freedom of choice, by directly discouraging people from using energy for purposes that they have previously used it for and would like to continue doing so, are likely to result in considerable public dissatisfaction. Examples include discouraging people from making out-of-town trips (or requiring the use of particular modes to do so), reducing the use of automobiles in favor of other forms of transportation, or instituting an "annual carbon allowance" as Great Britain is said to be considering.[104]

The reason for making this distinction is the difference in the political impact of these measures. In sufficiently wealthy countries where the change in energy costs may not have a large impact on the public, it may be possible for politicians to persuade their constituents to accept some measures involving (1) but it may be almost impossible to do so for those primarily involving (2). But in many less developed countries where prices of electricity, heating oil, and other forms of energy are already being subsidized due to strong popular demand, even increases in prices due to (1) are likely to be politically unpalatable. Even in wealthier countries, politicians are likely to be very cognizant of increases in energy prices that are likely to make the country less competitive internationally. They will probably favor price increases where they will not have a major impact on the price of exports and where there is no international source that could provide a

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[103] Although regulated industries often try to exaggerate the difficulties involved in meeting proposed regulations, it may be significant that the Electric Power Research Institute has carried out a new study that claims that it would take twenty years for the U.S. electricity utility industry, which emits about one-third of U.S. global warming gases, to reduce emissions to 1990 levels (Kyoto requires reductions below 1990 levels) regardless of how much the industry spends. Matthew L. Wald, *Study Questions Prospects for Much Lower Emissions*, N.Y. TIMES, Feb. 15, 2007, at C2.

[104] One of the most prominent "prescriptions" as to how emissions can be drastically cut includes an example of component (2) since it proposes that annual average miles driven per vehicle be reduced from 10,000 miles to 5,000 miles based on "urban design, mass transit, and telecommuting." Stephen W. Pacala & Robert H. Socolow, *Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies*, 305 SCIENCE 968, 970 (2004). To the extent that this is done through coercion rather than voluntary change (which is almost certain given people's widely observed reluctance to give up using their cars), this would be an example of component (2). An even more drastic proposal for actual individual emission rationing is reported under consideration in Great Britain. *See* David Adam, *Swipe-Card Plan To Ration Consumers' Carbon Use*, GUARDIAN UNLIMITED, July 19, 2006, *available at* http://www.guardian.co.uk/climatechange/story/0,,1823853,00.html.

substitute good or service at a lower cost. Electricity generation is probably a good example. Such increases have only an indirect effect on competitiveness.

Proponents of GHG control argue that the cost will be just a few percent of the GNP and that future growth will be many times the costs involved. Those who will have to pay those costs, particularly if it is not a very broad cross-section of the population, are likely to object strongly, however. To persuade them otherwise would require an advertising or information campaign of unprecedented scope and cost. These costs are not usually factored into the costs of emission control, and the public is more likely to see them as a tax that someone has proposed to impose on them, rather than a contribution of a small percentage of their future economic gains. Many in the developed world will also see global warming control as a type of often unpopular foreign aid since many of the costs of global warming may fall on less developed countries with high dependence on agriculture.

There are strong economic incentives not to reduce GHG emissions. The increasing use of fossil fuel energy to replace animal and human power has been one of the hallmarks of modern civilization. It has occurred because there are strong economic incentives to do so. These incentives could be changed by government actions, but they are so fundamental that these changes might prove to be very difficult to bring about. As illustrated by the current problems faced by many EU countries and Canada in meeting their Kyoto commitments, politicians would be required to maintain unusually strong resolve and actually implement the reductions, even as the population learns what the real effects of the measures would be on them. Under current circumstances, politicians can argue that higher energy prices are a result of the operation of the laws of supply and demand in the marketplace. But if markedly higher prices or energy use restrictions were imposed by politicians for the purpose of reducing global warming, they would be faced with a much more difficult situation.

It is difficult to see why politicians would be willing to force their constituents to adopt unpopular and expensive constraints on their activities, or why many of their constituents would not pursue every available loophole or alternative avenue to avoid observing the constraints that are imposed. In the case of type (2) measures, grandmothers may not agree that trips to see their grandchildren on the opposite coast can be dispensed with, particularly if politicians (and their possible future environmentalist supporters) do not fully explain in advance the degree of sacrifice that would be required. If the estimates of "needed" reductions in GHG emissions discussed in Part III.C, above, are correct, it appears unlikely that all the reductions could be implemented in type (1) ways but would require use of some type (2) measures as well. In other words, effective action under the Kyoto approach appears to assume that individual citizens would cooperate in ways that would involve significant sacrifices of personal freedom to choose.

Although global warming is perceived as the world's single largest environmental problem in the spring of 2007 by about one-third the U.S. population (and double the number who gave it the top ranking in 2006), there is little consensus as to what should actually be done about it.[105] Global warming has all the psychological characteristics (a long time horizon in human terms, uncertainty, familiarity with temperature changes, and no clear and visible effects that constantly remind people that there is a problem that needs to be solved) that are likely to keep it at a low priority level.[106] Elke Weber, of the Center for Research on Environmental Decisions at Columbia University, also believes that there are underlying psychological reasons why global warming does not scare people.[107] The economic costs of the large GHG emissions reductions required to meet current interpretations of UNFCCC goals would be enormous—so much so that very few countries would willingly undertake them, particularly if all countries did not.[108] Achievement is unlikely to occur given the difficulty of instituting and using weak international bureaucratic systems to cope with strong economic incentives to use fossil fuel energy and other processes that release GHGs.

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[105] Juliet Eilperin & Jon Cohen, *Growing Number of Americans See Warming as Leading Threat, Most Want U.S. to Act, but There Is No Consensus on How*, WASHINGTON POST, April 20, 2007. The survey reported in the *Post* article found that only one in five favor higher taxes on electricity to encourage conservation, and about a third support higher gasoline taxes. Sixty-two percent of those surveyed say the government should require power plants to reduce emissions of greenhouse gases. Forty-two percent think the government should require greater fuel efficiency for vehicles, and thirty-six percent want to require manufacturers to produce more efficient air conditioners, refrigerators, and other appliances. *See also* Andrew C. Revkin, *Yelling 'Fire' on a Hot Planet*, N.Y.TIMES, Apr. 23, 2006, § 4, at 14 (reporting on the unassuming urgency of the global warming problem).

[106] *Id.*

[107] Elke U. Weber, *Experience-Based and Description-Based Perceptions of Long-Term Risk: Why Global Warming Does Not Scare Us (Yet)*, 77 CLIMATIC CHANGE 103 (2006) (exploring the phenomenon of humans' risk perception of climate problems).

[108] See *infra* Part V.A for a discussion of the economic costs.

Because of very slow response times by many components of the earth's climate, the effects of GHG emission reductions will be a long time coming and will only gradually affect those changes that have already occurred. Proponents argue that the Kyoto Protocol is a useful first step down a long road, but given the larger picture, it seems reasonable to ask whether it is sufficient if the stabilization of GHG levels in the atmosphere and therefore the mitigation of global warming are not likely to meet current interpretations of UNFCCC goals.

In many ways, the Kyoto approach to global warming assumes that CO_2 and other GHGs are just another set of pollutants that need to be controlled. The approach taken in the Kyoto Protocol is the rollback approach used often in many previous pollution control efforts. Where reasonably priced alternatives exist or the costs of nonuse are not prohibitive, this approach has indeed worked well in many developed countries for other pollution problems. But because of the central role that fossil fuel use plays in modern civilization and that GHGs play in Earth's climate, GHGs are not just another set of pollutants. GHG emissions control therefore requires a careful reexamination of what it is that is to be achieved and what is the best means for doing so. The pollutant control approach is not only unlikely to succeed but is also extremely expensive as well as probably not meeting economists' larger objective of maximizing human welfare.[109]

5. Lack of Effective International Enforcement or Payment Mechanism

Voluntary international agreements often do not have much of a history of success. Even if there should be a follow-on to Kyoto, it appears unlikely that that it would be any more successful. The reason for this is that it is difficult, if not impossible, to conceive of a mechanism for ensuring compliance with any global scheme adopted.[110] And without an assurance of effective penalties or other incentives, there will be overwhelming incentives for nations to "free ride" on contributions by others.[111] Kyoto does not effectively address this

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[109] See *infra* Part V.A for a discussion of the economics involved.

[110] *See* Lee Lane, *Reflections on Transatlantic Climate Policy*, paper presented at Symposium on Climate Policy in the Coming Phases of the Kyoto Process: Targets, Instruments, and the Role of Cap and Trade Schemes, Brussels, February 20-21, 2006 (on file with author).

[111] *See* Scott Barrett & Robert Stavins, *Increasing Participation and Compliance in International Climate Change Agreements*, 3 INT'L ENVTL. AGREEMENTS: POLITICS, LAW &

problem for participating Annex I countries or for others. Presumably, the reason is that there was no way to do so. The idea that "moral shame" will somehow persuade large CO_2 emitters like the United States, India, or China to undertake costly and politically painful mitigation efforts appears highly dubious. But without strong international penalties or incentives, any Kyoto follow-on is equally likely to flounder at the cost of the additional time that it will take for this to become apparent to everyone involved. Presumably one way to provide incentives to the less developed countries would be to offer large incentive payments from the major economic powers. But who would be willing to provide them, given the "free rider" problem? The United States is not known for high levels of foreign aid, the budget category that these expenditures are likely to be lumped into, and which already is being used to further many other objectives. It appears equally unlikely that the participating Annex I countries would be willing to foot the bill by themselves.

6. Lack of Support from Major GHG Emitters

The lack of support by the United States and the lack of emissions reductions required of the rapidly growing countries of Asia pretty much doom the Kyoto Protocol in its present form from playing any meaningful role in controlling climate change. Without active GHG emissions reductions by at least India, China, and the United States, it is extremely doubtful that anything meaningful can be achieved. One reason that the United States is not participating is the lack of a contribution from the other two countries. This argues that the cause of global climate control would be better served by substituting a different approach based on incentives rather than governmental coercion, a sharing of the burden based on past and present contributions to the problems, and the ability to use a wider array of technological approaches to solve the problems. The advantage of incentives is that those faced with the lowest cost of control would do the controlling, rather than those who happen to have been allocated the most stringent quotas. Coercion is likely to result in more resistance than progress. And contributions based on the share of the problem caused would make the rationale explicit and possibly even "equitable."

ECON. 349, 358 (2003) (recognizing the importance of increasing countries' participation in reducing GHG emissions).

7. Weak Basic Rationale

One of the basic problems with the Kyoto Protocol is the lack of a careful rationale for the approach used. This appears to be one of the reasons that the United States has rejected participating in it. Viewed as a purely technical issue, the damages from CO_2 emissions are caused by the additional emissions to the atmosphere. A good case can be made that any emissions of CO_2, past or present, have had roughly the same adverse effects since the time that CO_2 concentrations exceeded "normal" levels. Although CO_2 is lost each year, primarily to the oceans, it now appears that this has adverse effects too.[112] A rough cut at an "equitable" system to allocate damages might be to calculate the total incremental anthropogenic CO_2 emissions since the diversion from "normal" levels for each country. This would result in the largest allocations to those countries with the greatest and longest standing emissions, but it would not exempt developing countries either.

Instead, Kyoto completely exempts developing countries and sets what appear to be arbitrary limits on emissions from developed countries. The "equitable" system just discussed would place a significant penalty on developing countries with large emissions and encourage them to cut their emissions while still placing the major burden on countries with substantial and longstanding emissions (like the United States). Although estimates of these previous emissions are inherently uncertain, it appears possible to make useable estimates and therefore country allocations. This approach would at least create a credible rationale for the allocation of the costs of climate control between countries.

8. Partial Exclusion of Nuclear Power and Exclusion of International Aviation and Shipping Fuels

The Kyoto Protocol excludes nuclear energy under two of the three "flexibility mechanisms" that can be used by participating Annex I nations to meet their commitments. Nuclear power is one of the few possible substitutes for fossil fuel power to supply base load power, so

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[112] *See* ROYAL SOCIETY, OCEAN ACIDIFICATION DUE TO INCREASING ATMOSPHERIC CARBON DIOXIDE: POLICY DOCUMENT 12/05 25-30 (2005), *available at* http://www.royalsoc.ac.uk/displaypagedoc.asp?id=13539 (studying the effects of atmospheric CO_2 on ecosystems in the oceans).

giving it second-class status further constrains the possible solutions to the climate change problem.

The Protocol also excludes any consideration of emissions from international aviation and shipping fuels. International aviation and shipping are both growing sources of GHG emissions, and their exclusion places an increased burden on the remaining sources.

9. A Brief Summary Concerning the Kyoto Protocol

Few voluntary international agreements have been successful in meeting their goals. Goals that can only be met with the active cooperation of most of the world's governments and people, including those that have not participated in the agreements or have not made any commitments to actively contribute, are particularly unlikely to be met. Agreements that have no effective enforcement mechanism are even less likely to succeed, especially when everyone has an interest not to cooperate. The Kyoto approach in general and the Kyoto Protocol in particular appear to be highly unlikely ways to meet worldwide goals for reducing GHG emissions in a timely or effective way. These goals are very demanding, and there is no reason to believe that the Kyoto approach would be an exception to previous experiences with voluntary international agreements.

IV. SOME ALTERNATIVE APPROACHES FOR CONTROLLING CLIMATE CHANGE

If the Kyoto Protocol—or even the Kyoto approach—will not prevent climate change or even mitigate it to the extent envisioned, and prevention or mitigation is something that humans want to achieve, what are some of the other tools available to control climate change, and how should they be evaluated? In order to answer this question, it is important to first examine the criteria to be used in determining the answer. Part I.A outlined the proposed evaluation criteria; this Part discusses the primary remedies, tools, and approaches that have received some attention and that are to be evaluated in this Article.

A. *Nonstabilized "Business-As-Usual" Carbonization and Adaptation (*R1*)*

This "remedy" assumes that no significant changes will be made to the current situation in which GHGs continue to be released into the atmosphere as rapidly as in the recent past and few are removed except through natural processes. This means increases in atmospheric CO_2 levels of two to three parts per million per year.

B. *Kyoto Management Plus Conventional Decarbonization Technology (*R2*)*

This remedy assumes continuation of the management approach provided by the Kyoto Protocol, but that only "conventional" technological approaches (*TA1*) plus nuclear power (which Kyoto does not encourage) are used to control climate change.

C. *Nonconventional Decarbonization or Sequestration (*R2a*)*

1. CO_2 Sequestration

Several alternatives have been proposed to increase the absorption of CO_2 from the atmosphere by plants.[113] CO_2, and presumably other GHGs, can also be artificially removed from the atmosphere and directly stored in a number of places. In addition, CO_2 can be removed from fossil fuel-burning emissions before reaching the atmosphere. This last option may not constitute geoengineering as the term is used elsewhere since it can be viewed as source mitigation, but this distinction will be ignored in this discussion.

a. *Using Artificial Sequestration (*RC*)*

A number of ideas have been suggested for the artificial sequestration of CO_2, including terrestrial, nonbiological sinks located in a number of geological formations (including depleted oil and gas fields, deep coal beds, and deep saline aquifers). In addition, there is the possibility of oceanic nonbiological sinks, using very deep areas of the oceans. Finally, there is the possibility of neutralizing the acidity of the carbonic acid resulting from dissolving CO_2 in water and disposing of the neutralized compounds into the ocean.[114]

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[113] *See generally* Keith, *supra* note 17, at 259-68 (reviewing various proposals to manipulate the climate, including increasing the amount of outgoing infrared radiation or increasing albedo); INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE [IPCC], CARBON DIOXIDE CAPTURE AND STORAGE: SUMMARY FOR POLICYMAKERS AND TECHNICAL SUMMARY 1, 2 (Bert Metz et al. eds, 2005), *available at* http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/ccsspm.pdf (describing how CO_2 capture and storage could help mitigate climate change).

[114] *See* Greg H. Rau et al., *Enhanced Carbonate Dissolution as a Means of Capturing and Sequestering Carbon Dioxide*, 2001 FIRST NATIONAL CONF. CARBON SEQUESTRATION 1-4,

b. *Enhancing Natural Sequestration (*RD/RE*)*

Although a wide variety of proposals have been made, the principal proposals for terrestrial biological sinks involve intensive management of forests or other terrestrial ecosystems to stimulate their removal of CO_2 from the atmosphere beyond what would otherwise take place naturally. The principal proposals for natural oceanic sequestration involve fertilizing the ocean surface with phosphate or iron in order to stimulate algae growth by supplying a biologically limiting nutrient (RE).[115] Some of the algae will ultimately fall to the ocean floor as organic matter, carrying carbon absorbed from the atmosphere with them. More algae falling mean more carbon sequestered.

D. *Engineered Climate Selection or Changing Earth's Radiation Balance Directly (*R3*)*

To the extent that there is a need for preventing or mitigating only the temperature-related effects of global warming, there is strong evidence that this can be done by altering Earth's radiation balance. This was discussed as long ago as 1979 by Freeman Dyson and Gregg Marland[116] and perhaps most prominently by a 1992 National Academy of Sciences global change panel,[117] which noted what appeared to the panelists to be its surprisingly great practicality. Other scientists have recently expressed interest.[118] There are a variety of proposals to change the world's temperatures by altering either the heat coming into the earth from the sun or changing the amount of heat reradiated back into space from the earth. It is important to note that this approach differs from the previous ones in that GHG levels in the at-

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available at http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/p24.pdf (describing the process of enhanced carbonate dissolution).

[115] *See generally* Ben Fertig, *Ocean Gardening Using Iron Fertilizer* (Aug. 2004), http://www.csa.com/discoveryguides/oceangard/overview.php (exploring the idea of using iron to sequester CO_2).

[116] Freeman J. Dyson & Gregg Marland, *Technical Fixes for the Climatic Effects of CO_2*, *in* U.S. DEP'T OF ENERGY, WORKSHOP ON THE GLOBAL EFFECTS OF CARBON DIOXIDE FROM FOSSIL FUELS (Report No. CONF-770385, 1979).

[117] *See* NAT'L ACAD. OF SCIS., *supra* note 18, at 100-09 (discussing the science of altering the heat balance through radiative forcing and radiative feedback mechanisms).

[118] *See* Broad, *supra* note 6, at F1 (describing the increasing populatiry of the sulfate aerosol proposal); Hanley, *supra* note 6, at A9 (reporting also on the method of sulfate aerosols in the stratosphere to slow warming); Wigley, *supra* note 6, at 452 (proposing the use of sulfate aerosols in the stratosphere to provide time for humans to mitigate warming through reductions in greenhouse gas emissions).

mosphere are not directly altered. Only three of these proposals will be discussed here in order to simplify the discussion, but it is highly likely that there are others of equal or greater merit that have or will be proposed. So these proposals should be viewed as illustrative of the possibilities available and not as a definitive list.

The Livermore papers[119] suggested and explored the feasibility of engineered climate selection approaches to altering Earth's radiation balance to affect climate. To counteract global warming, Teller et al. advocate allowing a little more of Earth's thermal radiation to pass out of the earth and/or allowing a little less of the sun's thermal radiation in.[120] To counter global cooling, they suggest allowing a little less of Earth's thermal radiation out and/or a little more of the sun's in. This discussion concerns only a few of these proposals, which will be referred to as "radiative forcing" in this Article, and is intended to in-

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[119] Edward Teller et al., *Active Climate Stabilization: Practical Physics-Based Approaches to Prevention of Climate Change* 1, 1 (Univ. of Cal. Lawrence Livermore Nat'l Lab., Preprint UCRL-JC-148012, 2002) [hereinafter Teller, *Practical Physics-Based Approaches*], *available at* http://www.llnl.gov/globalwarm/148012.pdf (preferring active technical management of the radiative forcing of the temperatures of the earth's fluid envelopes over the administrative management of atmospheric greenhouse gas inputs); Edward Teller et al., Active Climate Stabilization: Presently-Feasible Albedo-Control Approaches to Prevention of *Both* Types of Climate Change, Presentation to the Tyndall Centre and Cambridge-MIT Institute Symposium on Macro-Engineering Options for Climate Change Management, at slides 4-6 (Jan. 7-9, 2004), [hereinafter Teller, Active Climate Stabilization], *available at* http://www.tyndall.ac.uk/events/past_events/active.pdf (proposing the use of radiative forcing of Earth's temperatures); Edward Teller et al., *Global Warming and Ice Ages: I. Prospects for Physics-Based Modulation of Global Change* 1, 1 (Univ. of Cal. Lawrence Livermore Nat'l Lab., Preprint UCRL-JC-128715, 1997), [hereinafter Teller et al., *Physics-Based Modulation*], *available at* http://www.llnl.gov/globalwarm/231636.pdf (proposing the use of scatterers to reduce the effects of GHGs); Edward Teller et al., *Long-Range Weather Prediction and Prevention of Climate Catastrophes: A Status Report* 1, 3-8 (Univ. of Cal. Lawrence Livermore Nat'l Lab., Preprint UCRL-JC-135414, 1999), [hereinafter Teller et al., *Long-Range Weather Prediction*], *available at* http://www.llnl.gov/tid/lof/documents/pdf/236324.pdf (reporting on the progress of high technology forecasting, such as isolation modulation, as a means to address global warming); Lowell Wood, Earth Albedo Engineering: A Rio Convention-Indicated Approach to Mesoscale Climate Stabilization as Atmospheric CO_2 Levels Rise Toward the "Agricultural Optimum", Presentation to the Energy and Environment Study Group, at slides 8-14 (Apr. 7, 2005) (on file with author) [hereinafter Wood, Earth Albedo Engineering] (exploring the technical options available for modifying Earth's albedo); Lowell Wood, Geoengineering: Albedo Modulation Approaches to Preferred Climates as the Atmospheric CO_2 Level Rises Towards the 'Agricultural Optimum' Energy Modeling Forum's Workshop on Critical Issues in Climate Change, Snowmass, CO, July 26-Aug. 4, 2005 [hereinafter Wood, Geoengineering].

[120] *See* Teller et al., *Global Warming and Ice Ages*, *supra* note 21, at 9-12 (describing the use of scatterers to cool the climate in a way similar to the emission of sulfur particles from volcanic eruptions).

clude the most attractive proposals found in the Livermore papers involving the stratosphere and space.

1. Dispersing Sulfate Particles into the Stratosphere (*RF*)

As discussed previously in Part II.G.4, it is clear that sulfur-containing gases that reach the upper atmosphere from major volcanic eruptions cool the planet.[121] Human dispersion of such gases, presumably in a more optimized formulation, should have the same effect. Such approaches have been discussed in the Livermore papers, by the National Academy of Sciences,[122] and most recently by P.J. Crutzen.[123]

2. Optimized Radiative Forcing Using the Stratosphere (*RG*)

The idea in Remedy *G* is to add "optimized" particles to the stratosphere that would affect various parts of the thermal radiation passing through it.[124] The authors of the Livermore papers suggest using particular types of very fine particles that would reduce the amount of ultraviolet light striking the earth's surface, and offer a number of sug-

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[121] *See* Alan Robock, *Volcanic Eruptions*, *in* 1 ENCYCLOPEDIA OF GLOBAL ENVIRONMENTAL CHANGE 738, 741 (Michael C. MacCracken & John S. Perry eds. 2002), *available at* http://climate.envsci.rutgers.edu/pdf/EGECVolcanicEruptions.pdf ("Global sulfur emission by volcanoes to the troposphere is about 14% of the total natural and anthropogenic emission, thereby leading to a cooling influence at the surface.").

[122] *See* NAT'L ACAD. OF SCIS., *supra* note 18, at 448-54 (proposing the use of sulfuric acid aerosol to mimic the effects of radiation-reducing screens produced by volcanic aerosols).

[123] *See* Crutzen, *supra* note 6, at 212 (describing the use of "sunlight reflecting aerosol in the stratosphere").

[124] For the most recent such proposal, see Teller et al., Active Climate Stabilization, *supra* note 119. For global warming prevention, Teller et al. propose:

> • Controlled scattering of incoming sunlight back into space, by *sub-microscopic* minimum-feature-size
>
> • Dielectrics—e.g., [about 1 million tons per year of] ~ 100 nm sulfate aerosol-spherules [σ~V2 << λ6]
>
> • Metals—e.g., [about 0.05 millions per year of] "'UV chaff,'" super-P metal balloon-ettes
>
> • Resonant scatterers—e.g., [about 0.5 million tons per year of coated dye molecules] fluorescence options: strato-heating; brighter photosynthetic bands].

Id. at 8. For global cooling prevention they propose:

> • '[Long wave infrared chaff]': 10 μm mesh Al screen & 0.1 μm 'ribs' . . .
>
> • Semiconductor (e.g., Si)-walled super-P balloon-ettes . . . pass optical insolation; reflect Earth-sourced [long wave infrared] . . . .

Id. at 13.

gestions as to how they would be inserted into the stratosphere. The Livermore papers further argue that variations in the latitude where the substances are dispersed would make it possible to change global temperature distributions if desired, although this proposal is not part of the remedy considered here and could raise significant issues of who would lose and who would gain.

3. Optimized Radiative Forcing Using Space-Based Deflector (*RH*)

Some of the earlier Livermore papers also describe another option[125] involving the positioning of a specialized deflector between the earth and the sun designed to change the amount of sunlight reaching the earth. The authors believe that this could be built in a very flexible manner to allow for either increasing or decreasing the sunlight reaching Earth as required.

V. A COMPARISON OF SOME OF THE ALTERNATIVES FOR CONTROLLING CLIMATE CHANGE

It is surprising how little attention has been given to engineered climate selection approaches to global temperature control involving changing Earth's radiation balance, given the widely reported problems with the more "conventional" approaches. With a few exceptions, these geoengineering approaches have generally been ignored, dismissed out of hand, or, at best, recommended for more research.[126]

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[125] Technically, the deflector would be ideally placed at the L-1 (Lagrange 1) point between the earth and the sun and could be moved as needed from slightly off (to prevent ice ages) to directly on (to prevent global warming) the Earth-Sun line. The L-1 point is a point in space on a direct line between the earth and the sun, 1.5 million kilometers away from Earth. At that point, the gravity of the earth is balanced with that of the sun in such a way that anything placed there will, if gently nudged back into place every twenty-five days or so, orbit the sun once every year. This means that it will remain directly between Earth and Sun with almost no fuel expenditure. Currently there is a solar observatory satellite called SOHO there. The more technical specifications of this option, as proposed in Teller, Active Climate Stabilization, *supra* note 119, at 10, are:

- Total mass of 3,000 T emplaced over 100 yrs.—zero maintenance
- 1 Shuttle-launch per year of construction mass ($10^4 km^2$ area) [– Area of $10^4 km^2$]
- 'Raw' –cf. 10 MT previous design; ~0.01 MT 'dressed'
- ~30 µm-pitch (e.g., Al) metal screen—with ~25 nm 'ribs.'

[126] *See* Allenby, *supra* note 2, at 8-10 (lamenting the rejection of technological solutions to global climate change). One example can be found in IPCC, WORKING GROUP III, CLIMATE CHANGE 2001: MITIGATION: TECHNICAL SUMMARY (Rajenda

Although more research would be desirable, enough is known to suggest many of the advantages and disadvantages of these approaches. Some of the less attractive proposals are accorded only brief attention here. It should be noted, however, that the costs and benefits of various specific opportunities to reduce global warming vary considerably even within a single option, so that there may be "attractive" opportunities within remedies that do not appear to be generally attractive.

A. *Nonstabilized "Business-As-Usual" Carbonization and Adaptation (*R1*) and Kyoto Using Conventional Decarbonization Technology (*R2*)*

Remedy *1* (*R1*) is assumed to be the base case in this analysis, so that the benefits and costs of this "remedy" are assumed to be zero. Given the likely ineffectiveness of *R2, R1* currently appears to be the most probable approach that the world will follow, primarily as a result of inertia and the perceived lack of an imminent disaster. As outlined in Part II.H, this appears likely to result in increasing atmospheric CO_2 levels, increasing ocean acidity, and rising global temperatures.

A number of the characteristics of *R2* (shown as Remedy *B* in Table 2 and Figure 1) have already been discussed extensively in Part III, *supra*, since the emphasis under the Kyoto approach is what I have defined as "conventional" approaches. The results of some of the others, such as those discussed above in Part IV.C, could theoretically be counted under the Protocol, but are not usually actively considered for major roles in implementing it. One of the most apparent aspects of the "conventional" approach is that the outcome is uncertain since it depends not only on what actions various governments and individuals actually take, but also on how the resulting changes in emissions affect global temperatures. Current discussions of implementing Kyoto usually center around the use of a "cap-and-trade" approach, which has a good chance of minimizing the costs involved due to the inherent efficiency of using economic incentives. But since the methods to be used are necessarily unknown, the results are also

Pachavri ed., 2001), which has a very brief and general discussion of geoengineering approaches. It states that "although there appear to be possibilities" for it,

> human understanding of the system is still rudimentary. The prospects of unanticipated consequences are large, and it may not even be possible to engineer the regional distribution of temperature, precipitation, etc. Geoengineering raises scientific and technical questions as well as many ethical, legal, and equity issues. And yet, some basic inquiry does seem appropriate.

Id. at 43.

uncertain and hard to predict—clearly a disadvantage of these conventional approaches relative to those involving changing Earth's radiation balance, since they should yield much more direct control over global temperatures. In summary, Remedy *2* does poorly against most of the criteria, since it has negative efficiency, low cost effectiveness, poor environmental outcome, little equity, little flexibility to meet new conditions or possible global cooling, and places a great burden on participation and compliance. As noted in Part III, the current indications concerning implementability are not too encouraging.

The costs of implementing this approach are very much dependent on how rapidly the GHG emissions mitigation efforts are assumed to be implemented and on the percentage reductions assumed to be needed. Charles Kolstad and Michael Toman argue that marginal control costs increase with the percentage of carbon emissions controlled and may exceed $400 per ton for percentages in the range of 18% to 31% depending on the regions of the world involved.[127] Since considerably more control would be required to stabilize temperatures, their study would suggest that marginal costs would exceed $400 per ton. Carolyn Fischer and Richard Morgenstern analyze eleven different studies and also find that control costs increase with the percentage reduction in carbon emissions.[128] For abatement above 25%, marginal costs range from just under $50 to $350 per ton in the United States.

The reason that marginal costs vary with how rapidly mitigation is undertaken is that controlling GHG emissions can be undertaken most economically when the equipment that is producing the emissions needs to be replaced for other reasons. If the replacement is undertaken on a hurried or urgent basis without regard to these other reasons for replacement, the cost is much higher than those indicated earlier in this Section. If the replacement occurs for other reasons, the marginal cost is only the added cost of the GHG reduction features of the new equipment. If, however, the current equipment would otherwise not need to be replaced, then the entire cost of the replacement should be counted against the cost of controlling GHGs.

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[127] Charles D. Kolstad & Michael Toman, *The Economics of Climate Policy* (Res. for the Future, Discussion Paper No. 00-40 REV, 2001), *available at* http://www.rff.org/rff/Documents/RFF-DP-00-40.pdf.

[128] Carolyn Fischer & Richard D. Morgenstern, *Carbon Abatement Costs: Why the Range of Estimates?* 9 (Res. for the Future, Discussion Paper No. 03-42 REV, 2005), *available at* http://www.rff.org/rff/Documents/RFF-DP-03-42-REV.pdf.

When one is dealing with tens of thousands of very expensive thermal electric power plants or hundreds of millions of motor vehicles or hundreds of millions of home heating and air conditioning units, urgent replacement quickly becomes astronomically expensive. It is assumed in this Article that marginal costs are likely to be $50 to $400 per ton carbon. Lasky reviews a large number of cost studies that show estimated costs in this general range.[129] Although it is not always clear whether estimates are based on long-term replacement costs (just the added cost of replacing high-emission components with low-emission ones), most available estimates appear to be so based. One of the most comprehensive recent studies of actual opportunities for reducing emissions quotes costs of $100 per ton carbon.[130] John Deutch and Ernest Moniz estimate that a carbon tax of about $100 per ton carbon would equalize the cost of electricity from nuclear, coal, and gas sources.[131] This is significant, given that nuclear is one of the few technologies currently available that can substitute for fossil fuel-based base load power plants.

Although it carries its own environmental risks, there may well be a tradeoff that would have to be made between the risks of CO_2 emissions and nuclear power. Reuel Shinnar and Francesco Citro estimate that a carbon tax equivalent to $155 to $160 per ton carbon would be required to achieve a 70% reduction in CO_2 emissions over 30 years.[132] An earlier study found that stabilizing global CO_2 emissions would require a carbon tax in the range of $200.[133] The important point here is not the upper bound (which depends on both the speed of mitigation and the percentage reduction, and could rapidly reach astronomical levels under extreme cases) but rather that the marginal cost is not likely to be less than $50 per ton of carbon removed.

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[129] Mark Lasky, *The Economic Costs of Reducing Emissions of Greenhouse Gases: A Survey of Economic Models* (Cong. Budget Office, Technical Paper Series No. 2003-3, 2003), *available at* http://www.cbo.gov/ftpdocs/41xx/doc4198/2003-3.pdf.

[130] Robert Socolow, Keynote Address at the Scientific Symposium on Stabilisation of Greenhouse Gases, Stabilization Wedges: Mitigation Tools for the Next Half-Century, (Feb. 3, 2005), *available at* http://www.stabilisation2005.com/day3/Socolow.pdf.

[131] *See* John M. Deutch & Ernest J. Moniz, *The Nuclear Option*, 295 SCI. AM. 76, 81 (2006) (showing how a $100 per ton carbon tax would raise coal and gas prices to seven cents per kilowatt-hour, reaching parity with nuclear power costs).

[132] Shinnar & Citro, Supporting Online Material for *A Road Map to U.S. Decarbonization*, *supra* note 89, *available at* http://www.sciencemag.org/cgi/content/full/313/5791/1243/DC1.

[133] ALAN S. MANNE & RICHARD G. RICHELS, BUYING GREENHOUSE INSURANCE: THE ECONOMIC COSTS OF CARBON DIOXIDE EMISSIONS LIMITS 62 (1992).

Based on a broad review of the literature, Professor Richard Tol concludes that marginal benefits of carbon dioxide control of $15 per ton "seem justified," and $50 or more per ton "cannot be defended with our current knowledge."[134] But based on Tol's review, the net benefits appear to be negative and probably strongly negative for Remedy *B*. Although the approach, methodology, and values given by Nordhaus are different, his conclusions appear broadly consistent with Tol's findings since he finds that the benefit-cost ratio for the Protocol is 1/7.[135] On the other hand, the 2006 *Stern Review* reaches a very positive conclusion with regard to the net benefits of a regulatory decarbonization proposal.[136] It appears, however, that the *Review* used a much-below-market interest rate[137] and apparently ignored the large costs of public information and advertising campaigns to encourage the public to pursue energy conservation and to explain to them how to do so.[138] Neither of these assumptions appears justifiable and also has the effect of greatly reducing the costs relative to the benefits of the program they analyzed. The *Review* also assumed stabilization at 550 ppm CO_2e, which is unlikely to limit temperature increases to 2°C[139] and reduces the cost of the program compared to lower stabilization levels that have a greater likelihood of limiting the increases.

At the same time, it must be emphasized that both Tol's benefit estimates and the cost estimates used in this subsection are far from precise or generally accepted. Although they may well be the best currently available, the uncertainties are substantial. Readers are therefore encouraged to use this analysis as a way of thinking about the problem rather than as the last word on each of the values used.

One difference between Remedy *B* and the others is that *B* might result in reduced use of petroleum (depending on which actual re-

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[134] Richard S.J. Tol, The Marginal Costs of Carbon Dioxide Emissions 4 (July 7, 2003) *available at* http://www.defra.gov.uk/environment/climatechange/carboncost/pdf/tol.pdf.

[135] William Nordhaus & Joseph G. Boyer, *Requiem for Kyoto: An Economic Analysis of the Kyoto Protocol*, 1999 ENERGY J. (SPECIAL ISSUE: THE COSTS OF THE KYOTO PROTOCOL) 93, 93, *available at* http://www.econ.yale.edu/~nordhaus/homepage/Kyoto.pdf.

[136] *See* STERN, *supra* note 3, at 236 ("This resources-cost analysis suggests that a globally rational world should be able to tackle climate change at low cost.").

[137] *See Shots Across the Stern*, *supra* note 5, at 80 (citing Nordhaus's claim that the economics "are absurd").

[138] I received this information from a personal discussion with a *Stern Review* staff member.

[139] *See* Hare & Meinshausen, *supra* note 97, at 112 (noting that the European Union has set a global goal of not exceeding preindustrial warming levels above 2°C).

ductions in fossil fuel use were actually implemented). Since the later remedies on the list do not involve reducing energy use, it may be reasonable to include such benefits under Remedy *B* to the extent that petroleum use would actually be reduced. Presumably these benefits would primarily involve increased security resulting from decreased reliance on insecure or unstable sources of petroleum. It is nearly impossible to estimate these benefits because it is difficult to estimate the extent to which reductions in petroleum use would be used to meet Kyoto goals, the extent of the increased energy security, or its value. But these benefits of Remedy *B* should be considered significant, although nonquantified.

It should be noted that there are almost certainly some low-cost "conventional" opportunities in a wide range of areas, and some of them might even be comparable to some of the low-cost geoengineering options discussed above. There may even be some "conventional" opportunities where the private benefits exceed the private costs, although economists argue that they would have already been implemented in a perfectly competitive world if they were known to exist. The cost estimates shown in Table 2, Row B, *infra*, should be regarded as an attempt to bound the marginal costs needed to achieve the goals of the UNFCCC as interpreted by the EU. In other words, what is the cost of the most expensive "conventional" remedy that would have to be used to result in goal achievement (presumably that needed to limit temperature rise to 2°C) where the lower-cost remedies are used first? Because the CO_2 reductions under this option or remedy are varied and unpredictable given the learning curve that would undoubtedly evolve should implementation be attempted, there is no engineering estimate that can be made as to what the marginal cost would be. Rather, such estimates are at best guesstimates based often on model simulations. By contrast, most of the other options or remedies considered in this Article can be more reliably estimated using engineering cost estimates, since somewhat similar technologies are likely to be used on each project that might be implemented. Accordingly, the full range of estimated costs is shown for each of the other remedies, rather than the marginal cost.[140]

To the extent that there exist low-cost opportunities to lower GHG emissions using conventional means, these options are certainly worth pursuing. Although this will not be mentioned further, it almost goes

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[140] However, a dotted vertical line has been added to Remedy *B* in Figure 1 to show the full range of costs.

without saying. However, it appears highly unlikely, given the currently available research on marginal costs, that enough low-cost opportunities exist to meet the GHG reduction goals. Substituting more efficient light bulbs and reducing the power needed to keep appliances instantly available, if indeed these are very low-cost options, can only reduce GHG emissions a limited amount. But it is economically rational to pursue any energy efficiency project that can be justified in terms of the benefits of reducing the nontemperature effects of GHGs. Since the temperature effects can be controlled at very low cost using other options, these effects are unlikely to justify more than the lowest cost conventional measures.

Remedy *2* is particularly ill suited to situations where there is likely to be any significant change in the urgency of remedial actions because of the huge costs involved and the lengthy delays that would be needed to adjust the time frames, the country quotas, the particular regulations and incentives, and the actual investments by each individual country, industry, and individual. So to the extent that reducing climate change may be urgent (such as might be the case if there were an abrupt climate change due to a volcanic eruption or other cause), the conventional approach to reducing it becomes even less attractive than it otherwise would be, and perhaps even useless in the extreme case.

B. *Nonconventional Decarbonization or Sequestration (*R2a*)*

In general, CO_2 sequestration offers slightly more flexibility than the conventional approaches since implementation requires only initial agreement among those nations involved and individual citizens do not have to make decisions contrary to their immediate self-interest. But it is nevertheless difficult to see how it could be effectively used to respond to abrupt changes in conditions, particularly to counteract global cooling.

1. Artificial Sequestration (*RC*)

When using artificial sequestration, one difficulty is that fossil fuel-generated energy is often required, which generates more CO_2 and results in a lower net reduction. The costs of underground and oceanic injection (Remedy *C*) appear to be higher than many of the other remedies. The costs of carbonate dissolution in seawater, one of the lesser-known options, may be lower than those shown if the CO_2 source is located on the ocean and there is a nearby source of limestone. Greg Rau et al. quote costs as low as $25 to $160 per ton carbon in these favorable circumstances.[141] In those cases where concentrated CO_2 is sequestered it may be possible to release it fairly rapidly if global cooling threatened.

2. Enhancing Natural Sequestration (*RD/RE*)

The costs of intensive forestry (Remedy *D*) appear to be broadly similar but possibly higher than the "conventional" approaches. The approach offers very little flexibility to the extent that trees are involved because of their long life span, although it would presumably be possible to burn the trees if cooling threatened.

The costs of oceanic fertilization with minerals or nutrients such as iron (Remedy *E*) appear to be substantially lower than GHG mitigation but more than Remedies *G* and *H*. The impacts on the plant and animal life of the oceans is an area of concern but would presumably be generally positive since phytoplankton form the basis for most of the oceanic food chain. Most of the (relatively small scale) open ocean experiments carried out so far appear to support the general concept,[142] but have not always yielded encouraging results as to the ratio of the observed amount of carbon exported to the deep ocean per amount of iron supplied.[143] One estimate is that dumping huge amounts of iron into large swaths of the sea would absorb no more than 3% of annual CO_2 emissions from fossil-fuel burning.[144] New research, however, indicates that the ratio observed in nature may be an order of magnitude higher.[145] Although the implications of this new research for the use of Remedy *E* have not been worked out, it does suggest that much higher ratios are theoretically possible by using lower concentrations of iron and possibly adding other nutrients.[146] It

[141] Greg H. Rau et al., Poster Presentation at First National Conference on Carbon Sequestration: Enhanced Carbonate Dissolution as a Means of Capturing and Sequestering Carbon Dioxide 3 (May 14-17, 2001), *available at* http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/p24.pdf.

[142] A summary of the current scientific knowledge on the subject can be found in Fertig, *supra* note115.

[143] Quirin Schiermeier, Only Mother Nature Knows How to Fertilize the Oceans: Natural Input of Nutrients Works Ten Times Better than Manmade Injections, news@nature.com, April 23, 2007, http://www.nature.com/news/2007/070423/full/070423-8.html.

[144] *Id.*

[145] Stephanie Blaine et al., *Effect of Natural Iron Fertilization on Carbon Sequestration in the Southern Ocean*, 446 NATURE 1070-74 (2007).

[146] Inference based on references in *supra* notes 143, 145.

may be more expensive for humans to imitate nature in this way, but on the other hand further research may reveal variations on nature's approach that would be even more efficient.[147] This appears to be an extremely useful and urgent area for research.

C. *Engineered Climate Selection or Changing Earth's Radiation Balance (R3)*

A major advantage of options that change Earth's radiation balance is that they would allow global temperatures to be changed in either direction and determined relatively precisely and independently of GHG levels. Additionally, this could be done without the necessity for decisions by individuals against their immediate self-interest. Global temperatures could be maintained at what may be determined to be optimum on the basis of other criteria, while the economic advantages of higher-than-natural corresponding atmospheric CO_2 levels, such as reduced control costs and increased growth of some plants—including most domesticated crops[148]—are maintained. This has both good and bad results. It is good in that most of the adverse effects of global warming, including almost all those commonly discussed, could be eliminated rapidly and cheaply so that there would be no need to undertake expensive efforts to reduce GHG levels in terms of their climatological impacts. But the use of engineered climate selection would not affect the nontemperature change impacts of elevated GHG concentrations, which would therefore not be mitigated. So far, the most important nontemperature impact identified is elevated CO_2 concentrations on ocean acidification,[149] which in time would likely have adverse effects on calcifying marine organisms (including corals).[150] The extent and importance of these effects would therefore appear to be an important research issue in judging between the alternatives.

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[147] Schiermeier quotes one expert who believes that man cannot achieve nature's efficiency in this regard, but offers no justification for this dubious belief. Schiermeier, *supra* note 143.

[148] *See* Leanne M. Jablonski et al., *Plant Reproduction Under Elevated CO_2 Conditions: A Meta-Analysis of Reports on 79 Crop and Wild Species*, 156 NEW PHYTOLOGIST 9, 9-10 (2002) (citing the carbon and nitrogen allocation typical of domesticated crops as the primary reason for its reproductive response to CO_2).

[149] *See* ROYAL SOCIETY, *supra* note 112, at 1 ("There is a growing concern that as atmospheric concentrations of CO_2 continue to rise, the increasing acidity will have significant effects on the marine system.").

[150] See also Caspar Henderson, *Paradise Lost*, NEW SCIENTIST, Aug. 5, 2006, at 28-33, for a recent summary of the effects of acidification on the oceans.

1. Dispersing Sulfate Particles into the Stratosphere (*RF*)

The proof of concept for this remedy has already been provided by nature and has recently been further reinforced by P.J. Crutzen.[151] Based on observations of the climatic effects of adding volcanic sulfur to the stratosphere discussed previously in Part II.G, Remedy *F*—adding sulfate particles to the stratosphere—would clearly be effective against global warming (but not cooling), given the previously noted widely accepted experience with the climatological results of major volcanic eruptions, but could possibly be risky in terms of unintended environmental effects on the stratosphere, especially the ozone layer. One question, for example, is the effect of such particles on rainfall distribution. Luke Oman et al. suggest that the 1783 eruption of the Laki Volcano in Iceland may have resulted in a weak African and Indian monsoon that year.[152] Lowell Wood argues that particles would be emplaced well *infra* the ozone layer and that there is only slow vertical mixing, but does advocate "real air" measurements.[153] The importance of this option is that volcanic experience with this remedy has already demonstrated its strong climatic effects.

2. Optimized Radiative Forcing Using the Stratosphere (*RG*)

It is very reasonable to assume that humans could greatly improve on nature's efforts by optimizing this last approach (Remedy *F*) to the problems of global warming and cooling. The Livermore papers discuss the use of specialized materials in the stratosphere and find these approaches to be much less expensive and more effective than the "conventional" approach of trying to adjust the emission rates of GHGs. In fact, they state that the net costs of at least some of their approaches can be "strongly negative" (i.e., there would be no net costs, only benefits).[154] This is because of benefits their approaches may provide in other areas, such as reduced exposure to ultraviolet radiation and thus a reduction in skin cancer, greatly increased plant growth and agricultural productivity made possible by higher CO_2 levels created by the decoupling of CO_2 levels from climate, and even (if desired) a changed distribution of the heat energy from the sun fal-

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[151] *See* Crutzen, *supra* note 6.

[152] Luke Oman et al., *High-Latitude Eruptions Cast Shadow over the African Monsoon and the Flow of the Nile*, 33 GEOPHYSICAL RES. LETTERS L18711, at 2 (Sept. 30, 2006).

[153] Wood, Geoengineering, *supra* note 119.

[154] Teller et al., *Practical Physics-Based Approaches*, *supra* note 119, at 1.

ling on various parts of the world so as to make it more even. One of the more important additional benefits would be the ability to respond rapidly, and presumably effectively, to unanticipated and undesired changes in global temperatures in either direction, such as those that may occur as a result of major volcanic eruptions. Remedy *G* analyzes the stratospheric approaches advanced in some of the recent Livermore papers. Remedy *G* meets all of the criteria discussed in Part I.A, including environmental effectiveness, and would appear, based on the claims of its proponents, to be one of the best remedies discussed in this Article, even though they agree some research and development would be useful before it is actually implemented. It is particularly strong on the very important flexibility criterion as well as the economic ones. The only drawbacks appear to be that it does not address the adverse effects of elevated CO_2 levels on ocean acidification, that it could have possible adverse environmental impacts on the stratosphere, and that the impacts on rainfall patterns are not well understood (which is true of increasing CO_2 levels as well).

Although precise cost calculations are difficult to make, the equivalent cost per ton of carbon removed appears to be in the range of two to ten cents, compared to $50 to $400 for the more conventional approaches (see Table 2 and Figure 1). This estimate is based on costs presented by Wood[155] and an assumed offset of 10 gigatons of carbon per year, and appears to be consistent with David Keith's 2001 estimate.[156] Even if the costs are underestimated (as sometimes happens with new technological proposals) by one or even two orders of magnitude, the conclusions remain the same. According to its proponents, it meets the first aspect of the flexibility criterion by making possible timely adjustments of global temperatures to "fine tune" them towards any of the goals listed above in Part III.B. It seems to have a better chance than any of the other options (besides Remedy *H*) to control abrupt climate changes if advance agreement is reached as to what is to be done under specified circumstances, or if rapid agreement could be reached as to what is to be done under new circumstances. It meets the second aspect of the flexibility criterion

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[155] *See* Wood, Earth Albedo Engineering, *supra* note 119.

[156] David W. Keith, *Geoengineering and Carbon Management: Is There a Meaningful Distinction?, in* GREENHOUSE GAS CONTROL TECHNOLOGIES: PROCEEDINGS OF THE 5TH INTERNATIONAL CONFERENCE 1192, 1196-97, tbl.1B (David Williams et al. eds., 2001) *available at* http://www.ucalgary.ca/~keith/papers/41.Keith.2001.GeogineeeringAnd CarbonManagment.f.pdf (providing cost of mitigation estimates for various geoengineering methods, including space shields).

concerning the ability to control both global warming and cooling. And, according to its proponents, it even meets the third aspect of the flexibility criterion concerning the ability (but not the necessity) to change the geographic distribution of global temperatures. The benefits and costs are assumed to be what the Livermore paper authors say they are, although they are very close to those provided by Keith.[157] This may be a minor leap of faith since most of the Livermore papers are nonpeer-reviewed literature, but does not alter the clear effectiveness of this general type of remedy, as demonstrated by the climatic effects of major volcanic eruptions. Nordhaus argues that several geoengineering options are of such low cost that the costs can be ignored, so that the net benefits are roughly equal to the benefits from global warming control.[158] Presumably this would apply to this particular remedy, although it is not specifically mentioned by Nordhaus. On this basis, the efficiency of this remedy would appear to be strongly positive.

Although the basic physical and engineering principles needed to implement Remedy *G* appear to be on solid ground, there are many unanswered questions concerning whether this option really has been optimized, exactly how it would be implemented, exactly how much it would cost, and the nature and extent of nonglobal warming environmental effects that need to be answered before actual implementation could reasonably be undertaken. Proponents agree that some research and development would be useful before it is actually implemented. In 1999, Teller et al. suggested additional research and development of about $100 million to further refine this remedy and examine side effects;[159] their Tyndall presentation in 2004 mentions

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[157] *See* Keith, *supra* note 17, at 254 ("A 1% change in reflectivity might be brought about for about $500 million a year." (quoting President's Sci. Advisory Comm., *Restoring the Quality of Our Environment*, PSAC65 (1965))); Teller, *Physics-Based Modulation*, *supra* note 119 (providing annual cost estimates ranging from $200 million per year for metallic scatterers to $1 billion per year for dielectric scatterers).

[158] *See* William D. Nordhaus, *An Optimal Transition Path for Controlling Greenhouse Gases*, 258 SCIENCE 1315, 1317 (1992), *available at* http://cowles.econ.yale.edu/P/cp/p08a/p0829.pdf ("[G]eoengineering would introduce a hypothetical technology that provides costless mitigation of climate change. . . . Several geoengineering solutions have extremely low economic costs compared to conventional mitigation techniques and can therefore be treated as costless.").

[159] Teller et al., *Long-Range Weather Prediction*, *supra* note 119, at 3-4 (exploring the potential of a subscale proof-of-concept scattering system experiment "whose presence could be sensed and studied with sophisticated technical means but which would have completely imperceptible climatic consequences" for under $100 million).

about $1 billion.[160] Several of the other "nonconventional" remedies would also require additional refinement, but Remedy *G* might require more than most of the others given the numerous options and potential environmental risks that need more thorough exploration. The authors recommend a series of trials using scaled-down quantities to make sure that their theoretical calculations hold up in the real world and that they have not overlooked some negative environmental effects. In the case of the stratospheric options, the effects of these small-scale trials would be designed to dissipate in less than five years if any should be detrimental as a result of the movement of the materials of concern down out of the stratosphere. Therefore, in the proponents' view, these trials should not be considered a permanent alteration of the stratosphere even at a small scale. These trials appear prudent and would hopefully alleviate possible concerns that this novel approach is overly risky, as long as the approach could be abandoned when and if adverse new information is acquired. Wood lists some of the research that he recommends be undertaken.[161] Lee Lane, however, reports that no research is currently being undertaken and recommends that it should be.[162]

If the research and development were successful and subsequently implemented, this approach would break the relationship between CO_2 levels and temperature. Humans could increase CO_2 levels substantially, if that is otherwise the desired outcome, without incurring most of the costs imposed by unwanted global warming. And if CO_2 gets too low and/or an ice age threatens, temperatures could be rapidly increased to avert it. But it would not decrease the nontemperature effects of increased CO_2 levels in the atmosphere, such as increased ocean acidification.

To date, the principal scientific attack on the Livermore papers has come from Stephen Schneider on the grounds that varying insolation and albedo would "mess up" everyone's local (micro)climate.[163]

[160] Teller, Active Climate Stabilization, *supra* note 119, at 15 (discussing an experimental program to explore stratospheric scatterers in subscale scoped at $1 billion).

[161] Wood, Earth Albedo Engineering, *supra* note 119, at 16-17.

[162] LEE LANE, STRATEGIC OPTIONS FOR BUSH ADMINISTRATION CLIMATE POLICY 70-73 (2006).

[163] Email from Lowell Wood, Stanford University and Lawrence Livermore National Laboratory, to author (July 18, 2005, 21:44 EST) (on file with author); *see also* Stephen H. Schneider, *Earth Systems Engineering and Management*, 409 NATURE 417, 419 (2001) ("Because of the patchy nature of the greenhouse effect itself, even if we could engineer our stratospheric aerosol injections to balance on a [global] basis the amount

The proponents believe that research reported by Bala Govindasamy on this issue provides an adequate response to this question.[164] Govindasamy's paper reported on detailed modeling and argued that the "deep modes" of the current climate system maintain at least mesoscale climates worldwide without significant alteration, as the space- and time-averaged insolation is varied by a few percent in order to offset 2X or 4X increases in atmospheric CO_2.[165] The proponents believe that Govindasamy shows that their remedies would provide reasonably good compensation for any global warming due to higher CO_2 levels.[166] The proponents have tried to anticipate and answer many other potential criticisms of their proposals as well. A recent news report provides some interesting insights into the motivation for the Livermore papers and the internal questioning, research such as that mentioned above, and ultimately agreement that went on within the Laboratory concerning these proposals.[167]

3. Optimized Radiative Forcing Using Space-Based Deflector (*RH*)

A space-based deflector is likely to take substantially longer to put into place and to be much more expensive than stratospheric particles, but it would be just as effective in reducing incoming sunlight, much more permanent and flexible, have fewer environmental side effects, and involve lower maintenance costs.[168] Keith's 2001 estimate

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of [globally] averaged heat, . . . we would still be left with some regions heated to excess and others left cooler.").

[164] B. Govindasamy et al., *Geoengineering Earth's Radiation Balance To Mitigate Climate Change from a Quadrupling of CO_2*, 37 GLOBAL & PLANETARY CHANGE 157, 159 (2003) (reporting that even though varying insolation and albedo causes "residual climate change" to certain regions, "these residual climate changes are everywhere much smaller than the change from the quadrupling of CO_2 alone").

[165] *See id.* at 162 ("Comparison of surface temperature results by latitude band and season indicates that a reduction in solar luminosity may largely compensate for the impact of increased atmospheric CO_2, despite the differences in the latitudinal and seasonal pattern of these radiative forcings.").

[166] *Id.* at 166 (suggesting that "geoengineering may be a promising strategy for counteracting climate change"). For additional discussion of this general issue, see Morton, *supra* note 6, at 133-34.

[167] Anne McIlroy, *Going to Extremes To Fight Global Warming*, TORONTO GLOBE & MAIL, June 3, 2006, at A1 (describing the early debate between Edward Teller, a strong advocate for using geoengineering to fight global warming, and Ken Caldeira, a fellow researcher at Lawrence Livermore who was initially skeptical of Teller's theories).

[168] Keith, *Geoengineering and Carbon Management*, *supra* note 156, at 1194 (noting that while the "possibility of shielding the earth with orbiting mirrors is the most technologically extravagant geoengineering scheme," its costs are offset by fewer, less significant, and more predictable side effects that could be eliminated at will).

is that the equivalent cost per ton of carbon removed is between twenty cents and two dollars,[169] although there is no evidence that this is based on a careful engineering assessment of the problems involved. One of the more important additional benefits compared to Remedy *G* would be the ability to respond even more rapidly (presumably immediately if adequate planning and coordination were accomplished ahead of time) to unanticipated changes in global temperatures, such as those that may occur as a result of major volcanic eruptions, nuclear conflicts, or abrupt climate changes. It presumably would also avoid most or all of the possible environmental side effects that could result from placing particles in the stratosphere.[170] But it would involve something beyond what has ever previously been accomplished: namely, assembling and maintaining a large structure far out in space. Despite the recent problems with the space shuttle, there are no obvious reasons that this could not be done, but it might well require significant time as well as technical and other resources to accomplish. Only a very careful engineering study could fully estimate the costs involved. Since it would also take much longer to design, transport, and build, one possibility might be to consider this as a possible longer term, more permanent solution that could be built during a period when optimized stratospheric particles are used to control global temperatures as an "interim" measure.

D. *General Conclusions Concerning Alternatives for Controlling Climate Change*

Geoengineering is more than a little controversial, as illustrated by the disparity in views between Schneider and Michaelson. Schneider argues that although "adaptation alone may prove inadequate," he would

> prefer to reduce slowly our economic dependence on carbon fuels, rather than to try to counter the potential side effects with centuries of injecting sulphuric acid into the atmosphere or iron into the oceans. Laying stress instead on carbon management, with little manipulation of biogeochemical or energy fluxes in nature, is a much less risky prospect.[171]

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[169] *See id.* at 1196 tbl.B1 (providing cost of mitigation estimates for solar shields).

[170] *See id.* at 1194 (noting that "solar shields effect a 'clean' alteration of the solar constant" without the side effects of particle-based solutions).

[171] Stephen H. Schneider, *Earth Systems Engineering and Management*, 409 NATURE 417, 421 (2001).

Michaelson, however, argues that

> the response to the claim that geoengineering "just won't work" is to argue that such a claim is premature in practice and foolish in principle. Of course, the case for any new technology is "uneasy," and uncertainty will remain up until a geoengineering project is put into place, but such uncertainty is not sufficient reason to fail to initiate research now. Nor can we be daunted by the prospect of vast, unforeseen secondary consequences of tampering with the Earth's climate; again, it is too early to tell. Caution is wisdom—but inordinate skepticism flies in the face of a century of technological achievement.[172]

Considering only temperature-related effects, it is hard to find anything to like about Remedy *B* other than that it is already largely in place in terms of its structure, at least until 2012. As outlined above in Part III, continued substantial reliance on it is most likely to result in substantial global warming because of its ineffectiveness,[173] a dependence on individuals making decisions against their own self-interest, and a reluctance to search for better alternatives. Remedy *B* also appears useless as a way to control global cooling. And the economic efficiency of this option appears to be strongly negative. The other potential remedies (other than *A*—no change) range somewhere between *B* and *G* in their attractiveness. Remedies *E* through *H* appear to offer positive efficiency and to make lower demands on individuals for implementation, but have varying costs and environmental side effects. Option *G* appears to be equal to or better than all the other options under each criterion (although *H* offers lower environmental risks at potentially much higher costs in time and money), so would appear, with one important footnote, to be reasonably called a superior option for dealing with gradual global warming, despite Schneider's reservations concerning geoengineering options. There are many unanswered implementation questions, however, concerning whether this option really has been optimized, exactly how it would be implemented, precisely how much it would cost, who would pay for it, and the nature and extent of nonglobal warming environmental effects that would need to be answered before actual implementation could reasonably be undertaken. But there would appear to be a case for undertaking an early but limited research and development effort to answer the geoengineering implementation ques-

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[172] Michaelson, *supra* note 18, at 80 (footnote omitted).

[173] *See* RUDDIMAN, *supra* note 19, at 172-73 (describing what the world might look like under these circumstances).

tions *before* making large investments in any high-cost remedies that might be undertaken under the Remedy *2*. Remedy *G* can also be viewed as a rapidly implemented interim measure—while longer-term CO_2 reducing remedies are put into place and become effective—and as an emergency response measure in the case of rapid climate changes, such as major volcanic eruptions or nuclear conflicts.

Although there is less experience with using these options than with option *B*, the technical risks appear controllable through careful experimentation. In the unlikely event that such experimentation shows that all the permutations of option *G* have significant environmental side effects, this would suggest the use of option *H*. Rejecting geoengineering approaches because of their remaining technical uncertainties or unfamiliarity, as Schneider does, is not a conclusion based on careful analysis. The major footnote to this conclusion concerns mitigating the nontemperature effects of increases in GHG levels (Problem 2, as defined in Part I.B), which the radiative forcing approaches would not affect, but which will be discussed in more detail in Part V.F.2.

The experience to date with the Kyoto Protocol has not shown that approach to be effective in significantly reducing the growth of GHG emissions or stabilizing atmospheric CO_2 levels. There would obviously be considerable difficulty in reaching an international agreement to undertake geoengineering projects not covered by the Kyoto Protocol, although the same would be true of follow-ons to the Protocol. The advantage of the geoengineering approaches, however, is that once agreed upon, there is no need for individual cooperation by most of Earth's energy-using population, as would be required for effective, worldwide energy conservation or other mitigation efforts on the scale that would be needed to bring CO_2 emission levels back to less than "dangerous" levels. And if (as seems almost certain) there are major volcanic eruptions that send material into the stratosphere, nuclear conflicts that send soot into the stratosphere, or if there is a collapse of the ocean conveyor belt or other abrupt or unforeseen climate changes, there would appear to be no other feasible remedy that could effectively mitigate the effects of those events on climate. Careful preparations for geoengineering approaches involving Remedy *G* may be justifiable even if they are never used for reducing global warming, but merely as an insurance policy against abrupt adverse climate changes such as these.

Continued pursuit of only regulatory decarbonization (Remedy *2*) appears to be counterproductive given the implementation problems inherent in it. Unfortunately, an unintended consequence may be to discourage consideration of more effective measures during the long period needed for the major deficiencies of Remedy *B* to become evident to all. Thus, although regulatory decarbonization is strongly favored by many environmentalists, the net result of pursuing it alone may be to postpone effective action to control global warming for as long as it takes for the world to recognize that this approach is very unlikely to significantly decrease atmospheric GHG levels to the extent needed to reach the EU temperature limits, or even to decrease them at all.

E. *Other Management Approaches Besides Those Already Analyzed*

In Part I.C, several other possible management approaches besides those analyzed so far were briefly listed. The question now is how the conclusions above might differ if these other management tools were used. The analysis suggests the conclusions discussed below.

1. (*MA1a*) Business-as-Usual with Voluntary Decarbonization[174]

This management option involves purely voluntary efforts by individuals or corporations concerned enough to do something, either with or without public educational efforts to persuade them to do so. This option presumably eliminates the potential political backlash from angry constituents whose GHG-producing activities would be reduced. It should also result in the use of relatively efficient control measures. Similarly, only those willing to be internationally less competitive would undertake such solutions, presumably eliminating its political problems. Although such efforts are likely to have a positive effect and deserve to be encouraged, it appears unlikely that a purely voluntary effort would have a significant effect on one or more of the four problems, since the effects are likely to be very small compared to what would be required to meet the UNFCCC goals as currently interpreted. Kyoto was undertaken in large part because of a concern that purely voluntary actions would be unlikely to meet the UNFCCC goals. This seems unlikely to have changed.

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[174] *See supra* Part.I.C.1 (discussing this approach).

2. (*MA2b*) Decentralized Regulatory Decarbonization[175]

If one or even a few local jurisdictions (or even single countries) should decide to take a decentralized approach as a result of a political or judicial decision, such initiatives might result in progress toward solving a small portion of the larger problem originating in that local jurisdiction or jurisdictions. But unless only low-cost solutions were imposed, the results would likely be less efficient and effective than under the Kyoto management approach applied to the countries or jurisdictions involved, since they would presumably be the only ones to pursue this approach and would be limited to whatever control measures might be available under current national laws in the case of local jurisdictions. The costs would presumably be higher compared to *MA2a*, since a locally based approach is likely to be less efficient than one based on new national legislation tailored to minimizing the costs of control for these particular pollutants (such as by the use of economic incentives such as cap and trade), and a single-country solution is likely to be less efficient than one based on an international agreement such as the Kyoto Protocol.

This does not mean, of course, that decentralized decisions could not be used by local jurisdictions to "push" the political process at the national level by creating costly or otherwise unpalatable alternatives unless alternative political decisions were made at the national level. But since most of the projected increased emissions worldwide are expected to originate in rapidly growing countries that presumably would not be involved, it appears highly unlikely that GHG emissions would be sufficiently reduced to meet the EU/UNFCCC goal or even to make a noticeable change in atmospheric GHG levels using this approach. Most of the proposals at the state and national level in the United States assume that all the other states or countries would take equivalent actions; if, as appears much more likely, they do not, there would be no way to meet the EU/UNFCCC goal even if a state or country met its goal in terms of GHG emissions reductions.

3. (*MA2c*) Liability-Based Regulatory Decarbonization[176]

One or more countries could adopt liability laws or legal precedents that make it very expensive for companies to sell or use products with very high GHG emissions. Unless all countries adopted them

[175] *See id.*
[176] *See id.*

and had similarly effective legal institutions, the results would probably be less effective and efficient than under the Kyoto approach. Presumably only those countries with strong judicial systems, liability-based legal traditions, and strong motivation could effectively utilize this approach. In addition, such an approach is unlikely to result in the adoption of the lowest cost control options given that no one executive branch institution would coordinate the control efforts for that purpose.

As in *MA2b*, however, it is entirely possible that climate change torts could be used to "encourage" the political process to take other actions to solve the problem. But if this process actually determined the control measures used, the results would probably be less efficient and effective than under the Kyoto approach, and probably less than under *MA2b*. Most of the comments made above under *MA2b* concerning the difficulty in achieving the EU/UNFCCC goal appear to apply.

4. (*MA4*) International Approach Using All Available Technologies and Management Approaches[177]

The intention here is to fashion a replacement for Kyoto that corrects at least some of its major deficiencies.[178] The place to start is to correct the weak rationale for Kyoto. As outlined in Part III.C.7, a much more logical basis for such an international agreement would be the "polluter pays" principle, as opposed to the "rollback" approach with exemptions embodied in Kyoto. Under the former approach, those countries responsible for present and past GHG emissions would pay an amount based on the lesser of the damages these emissions have caused or will cause and the cost of solving the resulting problems.[179] Most likely, some allowance could be arranged for countries to spend a portion of what they would owe internally for cli-

[177] *See id.*.

[178] *See supra* Part III.C (discussing the major deficiencies of Kyoto).

[179] A related "Brazilian" proposal was actually considered in the negotiations leading to the Kyoto Protocol and has received some attention since. *See generally*, Emilio L. La Rovere et al., *The Brazilian Proposal on Relative Responsibility for Global Warming*, *in* BUILDING ON THE KYOTO PROTOCOL: OPTIONS FOR PROTECTING THE CLIMATE 157, 158 (Kevin A. Baumert et al. eds., 2002), *available at* http://pdf.wri.org/opc_chapter7.pdf (describing the innovative "Brazilian" proposal, which included a "complex methodology" for "distribut[ing] emission reduction burdens among countries—according to each country's relative responsibility for the global temperature increase").

mate control purposes. Where the damages and costs for past and present emissions are roughly the same, as in the case of CO_2, the amount paid by each country would presumably be proportional to their total anthropogenic emissions since the time that human-caused emissions started causing problems. Where past emissions cause less damage and cost less to control than current emissions, the total amount paid by each country would be the sum of the damages and costs from past and current emissions. These payments, in turn, would be used to provide incentives for the development and application of technologies that reduce GHG emissions. Because all countries that have emitted GHGs that have failed to dissipate in noninjurious ways would be obligated to pay, all such countries would have an incentive to reduce emissions. Although the payments would be mandatory, the emission decisions would be voluntary. In the case of CO_2, all emissions since the time that atmospheric levels of CO_2 started to rise would be included, because these emissions are either still in the atmosphere or have been absorbed by the oceans (causing a deleterious effect on ocean acidification). Funds generated by these mandatory payments could be used to pay for the least expensive and most effective remedies—including engineered climate selection, nuclear power, incentives to reduce CO_2 emissions from air travel, and public educational efforts aimed at where they are likely to be effective—regardless of where these remedies occur or what technologies they use.

It is important that this "ideal" successor to Kyoto be fully enforceable. One critical design issue would be how to establish fair and equitable payments for emissions. The ideal approach would be to set levels that would just accomplish the desired goals—for instance, a limit of 2°C on world temperature increases and a corresponding (but as yet unestablished) goal for limits on ocean acidification. If the temperature goals were to be achieved using stratospheric radiative forcing only, the fee levels would presumably be very low—probably so low that such a complicated agreement might not be worth pursuing. If, on the other hand, a serious effort were undertaken to prevent ocean acidification, much higher levels would be required. It would be important to allow some flexibility so that prices could be changed if goals were or were not being met. Such an approach would encourage an incentive approach rather than a coercive approach to climate change control. Individuals and nations could decide whether to burn and pay, or use alternatives and not pay. They could also choose whether to accept financial assistance from the fund.

It must be emphasized that such a proposal would not solve all the problems of Kyoto. The principal remaining difficulty would be the high cost of preventing ocean acidification and the reluctance of people and governments to pay that cost. But if the world wants to reduce global GHG emissions, this proposal may offer a possible way forward toward that end, and might provide a basis on which the nations of the world could agree. All countries would be liable, although most (but not all) of the costs would still be paid by the developed world.

F. *Conclusions with Respect to Specific Climate Change Problems*

Part V.D summarized the general conclusions regarding efficiency and effectiveness of each remedy for the climate change problem as a whole. This Section applies those conclusions to suggest solutions to each of the four specific climate change problems delineated in Part I.B and in Tables 1 and 1a. Table 1 presents the results in the form of words; Table 1a uses the numbers from Table 2 to provide rough semi-numerical estimates of the effectiveness and cost of the four remedies to each of the four problems.

1. Gradual Increase in Global Temperatures (Problem *P1*)

A gradual increase in global temperatures has benefits as well as costs. The benefits are primarily that fewer humans will be subjected to cold temperatures and that some of the less useable Arctic areas will be more available for human use. The costs have been widely described by those concerned about global warming, but are reduced by the ability of humans to adapt to gradual changes.

The general conclusions outlined in Part V.D apply to this problem without change, so that Remedy *G*—adding optimized particles to the stratosphere—appears to be the superior remedy. Gradual increases in global warming could most efficiently and effectively be controlled using one of the radiative-forcing remedies. Attempts to control global warming through GHG control are unlikely to be successful because of the lifestyle changes required and high costs involved. The principal result of efforts to do so may be to delay effective action. Radiative-forcing remedies are among the few realistic alternatives available. They could best be carried out on an internationally cooperative basis, but could also be implemented on a "go-it-alone" basis at the risk of possible international condemnation.

2. Nontemperature Effects of Higher Atmospheric GHG Levels (*P2*)

Some of the nontemperature effects appear to be positive rather than negative; the positive ones actually favor the use of Remedy *G*, since it would not disturb the increasing atmospheric CO_2 levels. The primary example is the positive effect of elevated CO_2 levels on some plant growth. Presumably, both those plants whose growth is stimulated by higher CO_2 concentrations, as well as the animals and humans who consume them, will be better off by such higher concentrations. Current research suggests that cultivated crops and some weeds[180] may indeed benefit, though perhaps at the expense of other plants that are not stimulated by higher CO_2 levels. The stimulation of cultivated crops may be a major benefit to humans. The major adverse, nontemperature-related effect of elevated GHG levels appears to be increased ocean acidification, but others may be documented in future years. Any of the remedies other than *A*, *F*, *G*, and *H* can be used to decrease or control the growth of atmospheric CO_2 levels, and therefore ocean acidification. Remedy *C*, (artificial CO_2 sequestration), Remedy *D* (intensive forestry), and Remedy *E* (ocean fertilization) can be used to directly remove CO_2 from the atmosphere. The capture and use of CO_2 for enhanced oil recovery and the addition of limestone or other alkaline minerals to streams of newly generated CO_2, or possibly directly to the oceans, may be somewhat lower in cost than other options in limited geographical settings. The Royal Society argues that using limestone is infeasible on an oceanwide basis,[181] but does not comment on its use in CO_2 streams and does not provide cost estimates or other bases for judging this. Furthermore, it provides only vague cautionary comments concerning the possibility of iron fertilization of the oceans.[182]

Therefore, many questions appear to need answers: What would be the benefits gained from increased output from cultivated agriculture? What would be the cost of ocean neutralization using limestone? And to what extent would large scale phytoplankton fertilization increase carbon dioxide removal from the atmosphere and the

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[180] *See* Henry Fountain, *Climate Change: The View from the Patio*, N.Y. TIMES, June 4, 2006, § 4, at 16 (noting that some weed-like plants and certain tree species thrive in an atmosphere rich in CO_2).

[181] *See* ROYAL SOCIETY, *supra* note 112, at 37 (suggesting that practical concerns, such as transport and processing costs, as well as unknown environmental effects, militate against this approach).

[182] *Id.* (noting that this approach may also exacerbate chemical changes to the ocean and have potentially negative biological impacts).

oceans in the longer term and with what effects on ocean ecosystems?[183] Despite the efforts by the Royal Society to discuss remedies,[184] we may still be in the early stages of analyzing what can and should be done about ocean acidification. Since all the current CO_2 emission mitigation strategies have been designed to treat Problem *P1*, some effort would appear to be needed to refine them for treating ocean acidification.

The ocean acidification problem is likely to be the most difficult of the problems identified in this Article because of its potentially high cost, many unknowns, and relative invisibility to most humans. This is illustrated by the views of Ken Caldeira, a prominent scientist in the area of ocean acidification and one of the authors of the Royal Society report. He has suggested that ocean acidification can really only be addressed by avoiding almost any further CO_2 emissions since he believes any net emissions will have an adverse effect.[185] He has suggested a 98% reduction from current emission levels,[186] apparently assuming that other natural forces reducing atmospheric CO_2 levels might counteract the remaining 2%. The Royal Society report and Caldeira cite the high cost and practical difficulties of geoengineering approaches toward mitigating the chemical effects of increased atmospheric CO_2 concentrations on the oceans.[187] But as noted in Part III, decreasing CO_2 emissions will be a difficult and at best a very slow undertaking. Reducing them by 98% does not appear to be within the realm of realistic possibility in the current world. But not reducing CO_2 emissions will result in the extinction of the world's coral reefs, Caldeira argues.[188] Surely before this is allowed to happen it

[183] For a discussion of some of the scientific issues implicated by ocean neutralization strategies, see generally SCOR/IOC Symposium Planning Comm., *The Ocean in a High-CO_2 World*, OCEANOGRAPHY, Sept. 2004, at 72.

[184] *See* ROYAL SOCIETY, *supra* note 112, at 37.

[185] *See, e.g.*, Ken Caldeira, What Corals Are Dying To Tell Us About CO_2 and Ocean Acidification, lecture paper for the Eighth Annual Roger Revelle Commemorative Lecture presented by the Ocean Studies Board of the National Academy of Sciences (Mar. 5, 2007); *see also* Elizabeth Kolbert, *The Darkening Sea*, NEW YORKER, Nov. 20, 2006, at 70.

[186] Caldeira, *supra* note 185, at 9, 14.

[187] See ROYAL SOCIETY, *supra* note 112, at 37, for a discussion of using limestone to reduce ocean acidity. This characterization of Caldeira's views on both using limestone and other geoengineering approaches is based on a personal discussion with him on March 5, 2007.

[188] Caldeira is quoted as stating that "[c]oral reefs will go the way of the dodo unless we quickly cut carbon-dioxide emissions." Press Release, University of Illinois at Urbana-Champaign, Regardless of Global Warming, Rising CO_2 Levels Threaten Ma-

would be worthwhile to carefully reexamine all available geoengineering options, including those rejected by the Royal Society and Caldeira, since these would appear to be the only realistic options available that might satisfy Caldeira's concerns as to the effects of ocean acidification.

Although it has not really been demonstrated, this Article will assume that a careful analysis would show that preventing ocean acidification that would substantially damage the Earth's coral reefs or other marine ecosystems is worthwhile from an economic viewpoint. This is by no means clear and deserves much further study, but appears to be the most conservative assumption under current circumstances of uncertainty. It does appear likely that the most effective remedies are those that can be implemented without the need for changes in personal lifestyle decisions.[189] That would suggest primarily Remedy *E* (ocean fertilization), or Remedy *C* (artificial CO_2 sequestration), or possibly the use of limestone to neutralize the acidification caused by the higher levels of CO_2. Fertilizing the oceans appears to be effective in reducing atmospheric CO_2 levels and is one of the lower cost remedies for reducing atmospheric CO_2, but there is a need for research to greatly increase its effectiveness in exporting carbon to the deep ocean.[190]

Another important question is whether the use of Remedy *E* might directly reduce ocean acidification in the ocean layers in which phytoplankton live. Increased CO_2 removal by fertilized phytoplankton would presumably decrease concentrations of carbonic acid in these waters. This would likely trigger increased absorption of CO_2 by the oceans from the atmosphere in order to maintain chemical equilibrium and would lower atmospheric concentrations, but might nevertheless directly result in increased ocean pH levels as well. If so, Remedy *E* would be (1) an attractive option for lowering atmospheric CO_2 concentrations and, indirectly, ocean acidification; (2) the most attractive option for directly reducing ocean acidification; and (3) an interesting opportunity to increase ocean productivity, since phytoplankton forms the base of much of the oceanic food chain. This would seem to be a very useful area for further research. Artificial

rine Life (Mar. 8, 2007), *available at* http://earthobservatory.nasa.gov/Newsroom/MediaAlerts/2007/2007030824507.html.

[189] As previously discussed in Section III.C.4.

[190] See *supra* Part V.B.2.

CO_2 sequestration appears to cost much more, but it has fewer uncertainties.

3. Potential for Triggering "Tipping Points" (*P3*)

Although not widely discussed in the popular literature, this may well be the real danger of global warming since the resulting changes, if they occur, may be sudden and catastrophic in nature, and may be very difficult for humans or other life forms to adapt to. It appears reasonable that the risks from "tipping points" or other abrupt climate changes may be proportional to global or regional temperature changes. The lower the increase in temperatures, the lower the chance that a "tipping point" will be hit. If global temperatures could be held at levels typical for interglacial periods, presumably the chances would be even less based on evidence from previous such periods. But conversely, any time that a higher "target" temperature is adopted, the risk is presumably increased. Thus, failure to actually achieve a given goal or target may carry with it an increased risk of abrupt climate change. The EU and others have decided that an increase of less than 2°C does not carry with it significant risks,[191] but there is no way to know whether this is actually the case without carrying out the experiment. Rather, it appears more plausible that risk increases along with any increase in temperature, notwithstanding targets for acceptable temperature increase. So if, for example, the Kyoto approach does not achieve a particular objective, there is likely to be some increase in the risk relative to the situation if it were met.

Since this Article has argued that the Kyoto approach is unlikely to meet many of the current targets, it is important to ask which remedies may offer something useful if it becomes evident that a particular "trigger point" is about to be hit or an abrupt climate change is about to occur. In this case, among those remedies discussed in this Article, only the radiative-forcing ones might be implemented rapidly enough to control global temperatures and thereby avert the pending risk. It would appear feasible to use radiative-forcing remedies in a "rapid response" mode to greatly reduce these risks if advance preparations are in place. The issue here is the ability to react rapidly enough to signs that a "tipping point" is approaching so as to avoid actually triggering it. All of the remedies have the potential to curb

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[191] Press Release, EU, Limiting Global Climate Change to 2 Degrees Celsius (Jan. 10, 2007), *available at* http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/07/16.

the gradual increase in temperatures, but only F, G, and H appear to have the flexibility to actually take evasive action if a "tipping point" should appear imminent.

Implementing rapid changes in global GHG emissions in response to unexpected events is next to impossible. Because of its extreme flexibility, Remedy *H* has perhaps the greatest potential, followed by Remedies *F* and *G*. It is important to note that these remedies would have to be in place and ready to go in order to be useful in most "rapid responses," such as those envisioned in this paragraph and in Part V.F.4, *infra*. Waiting until the need becomes evident to make these preparations would make an effective response more problematic. In the case of Remedy *G*, being in place and ready to go involves carrying out the further development work discussed in this Article—i.e., building international agreement as to how this remedy would be employed if needed and arranging for the needed manufacturing and delivery means. In the case of Remedy *H*, it would mean actually building the solar deflector and building a command and control capability to use it effectively. Remedies *B* through *E* have very little to nothing to offer with regard to this problem.

4. Short-Term Cooling from Major Volcanic Eruptions and Nuclear Conflicts (*P4*)

Because of the unexpected nature of such events and the need to respond in a very short period of time if global cooling is to be avoided, only Remedies *F, G*, and *H* have the potential to play a useful role in responding. *H* is probably more useful than *G*, assuming that it could be built in time, because of the possibly lower lag time required to move a deflector than to launch particles into the stratosphere. Depending on the particles used, there might also be conflict with the sulfur compounds emitted during a volcanic eruption. Because significant global cooling probably has greater adverse effects than warming, and because of the risk that short-term cooling could turn into long-term cooling—even an extremely destructive ice age—the benefits of avoiding short-term cooling appear to be greater than often realized.

G. *Implications for the Choice of Remedies*

There would appear to be two conclusions from this analysis.

First, the participating Annex I nations appear to have selected one of the more difficult, expensive, and probably ineffective approaches—the Kyoto Protocol—to climate change control examined in this Article. If it could be fully and effectively implemented and expanded upon in future agreements, Kyoto might help to control ocean acidification (problem *P2*), but the available evidence indicates that all the other presently known climate change problems could be mitigated more rapidly, cheaply, efficiently, and effectively using engineered climate selection involving radiative-forcing—i.e., Remedy *G*, or possibly Remedies *F* or *H*. Even if effectively implemented, Kyoto would not provide protection against global cooling from major volcanic eruptions or nuclear conflicts (Problem *P4*) or the ability to evade "tipping points" (*P3*) if not recognized decades in advance. However, Kyoto does appear to be more effective and efficient than most of the alternative management tools examined in Part V.E, with the exception of a "go-it-alone" strategy involving radiative forcing.

Second, an efficient and effective solution would seem to be active pursuit of both geoengineering approaches involving radiative forcing, as well as a new effort to reduce ocean acidification, with immediate priority given to the former in order to rapidly solve what are potentially the most critical problems. Although significant efforts would be needed in order to fine tune the proposals to implement these geoengineering approaches, to build an international mechanism for making decisions, and to manufacture and launch the needed material and hardware, this approach could be used to rapidly reduce the risks of adverse feedback and tipping point problems due to global warming and global cooling from major volcanic eruptions or nuclear conflicts, and to rapidly stabilize global temperatures at any desired level. At the same time, the current GHG emission-control efforts could be refocused on the problem of reducing ocean acidification, with an early review of how acidification can best be mitigated and how the present international GHG emission-control efforts could be modified to make them much more efficient and effective for this new (but probably closely related) purpose.

The net result would be much earlier and more efficient control of three of the more detailed problems and at least the same progress (or lack thereof) in controlling ocean acidification as under the Kyoto approach (Remedy *B*). This would appear to provide significant gains and no losses compared to the Kyoto-only approach. This should also allow some time to better understand ocean acidification and to design and carry out a carefully crafted program to reduce it.

Several suggestions have been made concerning those geoengineering approaches that appear to be the most efficient and effective ways of reducing acidification, but it is clear that the problem deserves much greater attention and research. The problem of increasing global temperatures could theoretically also be solved by carbon dioxide emission controls, although it is doubtful how effective this approach would be. If such emission controls were used, the place to start would appear to be implementation of the lowest cost options first, while possibly delaying the more expensive ones until the problem is better understood. Such a delay would be economically rational given the sensitivity of the costs of carbon dioxide emissions reductions to the rapidity with which they occur. Substituting lower emission technology would be much cheaper if the goods in which the technology is embedded need to be replaced anyway due to old age or technological obsolescence. T.M.L. Wigley provides some atmospheric modeling along these lines.[192] This approach might also provide time to build a better replacement for Kyoto that remedies some of its most glaring problems.

The proposed priorities among the various remedies are shown in Tables 1 and 1a. The rationale is as follows: Remedy *G* appears to be very inexpensive and very effective in rapidly solving all climate change problems other than ocean acidification. Therefore, it is given the highest priority, or 1.

It has been demonstrated on a small scale that oceanic phytoplankton growth and CO_2 absorption can be increased by using Remedy *E* (ocean fertilization). This would be significantly more expensive than Remedy *G*, but much less than Remedy *C*, and appears to be the most attractive of the carbon sequestration approaches. It should also increase the productivity of the seas. So it is accorded a priority of 2, but with some questions concerning how humans can efficiently imitate nature in stimulating phytoplankton to export carbon onto the sea floor.

Ocean acidification can be addressed directly using limestone either to neutralize those streams of CO_2 near oceans and sources of limestone or to advance oil recovery, but this is much more expensive and would be feasible only in limited geographical areas. Remedy *C* is thus accorded the third highest priority, or 3.

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[192] *See* T.M.L. Wigley, *A Combined Mitigation/Geoengineering Approach to Climate Stabilization*, 314 SCIENCE 452, 452-54 (2006). More specifically, Wigley concludes that stratospheric geoengineering "could substantially offset future warming and provide additional time to reduce human dependence on fossil fuels and so stabilize CO_2 concentrations cost-effectively at an acceptable level." *Id.* at 452.

If it appears efficient to further reduce ocean acidification beyond what could be achieved with Remedy *E*, it would also appear that the most efficient remedies would involve CO_2 sequestration somewhere other than the ocean, since this could be done without worldwide cooperation. If it appears efficient to go beyond what CO_2 sequestration can efficiently accomplish to reduce ocean acidification, emission controls would be required as a last resort, hopefully under something similar to *MA4*. So this approach is accorded a priority of 4.

Whether ocean acidification reduction is worth pursuing beyond purely voluntary efforts would appear to be the most difficult analytical issue concerning the most efficient and effective solutions to climate change problems. There would appear to be two major issues. The first is the question of how much confidence one should have in the Royal Society report conclusions.[193] Despite the eminence of its authors, should the world really spend many trillions of dollars reducing ocean acidification on the basis of a single report, no matter the source? Surely it is worth a small percentage of such expenditures to re-check and re-analyze the report's conclusions and even initiate new experiments to verify its critical points.

The second major issue is whether the economic benefits of ocean acidification reduction would exceed the costs. An economic evaluation of the issue based on currently available information depends critically on the value of avoiding further ocean acidification offset by the value of the positive effects of CO_2 buildup in the atmosphere. The Royal Society report suggests that if the world follows a business-as-usual approach with regard to the buildup of CO_2 in the atmosphere, the resulting ocean acidification would in time have very severe effects on the oceanic ecosystem.[194] This could indeed inflict great damage on humans as well. Given the potentially very large cost of mitigating this effect, a greatly expanded research program and analytical effort is crucial to making an informed decision on whether and how rapidly to proceed with these very expensive CO_2 mitigation efforts.

Assuming that a decision is made that CO_2 mitigation is worthwhile because of these effects, the inexpensive stratospheric geoengineering approaches, which would hopefully already be underway,

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[193] *See* ROYAL SOCIETY, *supra* note 112, at 39-42 (detailing the "significant adverse effects of ocean acidification" and recommending action to address the problem).

[194] *See id.* at 39 (noting the rapid rate at which ocean pH levels will decrease in response to current emission patterns).

should prove to be a wise investment since they would reduce global warming until the ocean-acidification mitigation efforts took effect and would provide an insurance policy against abrupt adverse climate changes in either direction. In the case where a decision is made to proceed with conventional CO_2 emission reduction after Remedy *G* has already been implemented, the relatively small added costs of Remedy *G* would not be lost; all of the problems except ocean acidification would have been addressed earlier. In addition, the added capability to address problems *P3* and *P4* would presumably have proved useful in and of itself. Finally, it should be noted that without advance development, planning, international agreements, manufacturing, and delivery systems, Remedies *G* and *F* could not fulfill these shorter-term climate control functions.

VI. LIKELY MAJOR OBJECTIONS TO ENGINEERED CLIMATE SELECTION AND OTHER GEOENGINEERING REMEDIES

Assuming that any remaining technical problems in implementing engineered climate selection and other attractive geoengineering remedies could be resolved through a research and development program, the primary objections to these remedies are likely to be philosophical, legal, governmental, and strategic, as well as concerns about the risk of unintended consequences.[195]

A. *Philosophical Objections*

The major philosophical argument is likely to question whether humans should take direct management responsibility for determining global temperatures and GHG levels in the atmosphere. Although humans have been exerting an increasing effect on temperatures and GHG levels, it has heretofore been left to nature rather than humans to determine the outcome of this important aspect of the environment. The argument is likely to be that it is not acceptable to change nature by changing Earth's radiation balance or atmospheric GHG levels directly. It seems to be generally agreed that it is acceptable to change global temperatures by increasing or decreasing GHG emissions as long as it does not involve overt decisions. In other words, it has until recently been acceptable to increase GHG emissions as long as the increase is done for nonclimatic reasons, such as human gain or

[195] For a much more comprehensive discussion of the first three of these and other likely objections, see Michaelson, *supra* note 18, at 122-38.

convenience, and the effects were generally unknown. Similarly, it has been acceptable to decrease GHG emissions to an earlier level since this merely rolls back some of humankind's effects on the environment. But some may argue that it is not acceptable to deliberately remove GHGs already in the atmosphere or to change Earth's radiation balance directly, even though such an action would be for exactly the same purpose—to decrease global warming. That, it may be argued, would be interfering with "nature." A very good case, however, can be made that human-induced GHG releases are already interfering with "nature," as would proposed reductions, just in a less overt and less effective way. And directly managing global temperatures and GHG concentrations focuses attention on an environmentally important issue—the optimal temperature regime and GHG concentrations for the earth.

An additional aspect of this argument is that although human activities have brought about a number of adverse unintended consequences as a result of economic development, humans heretofore have responded to these problems by finding new technical, scientific, and natural resource solutions without significantly reducing human welfare. The use of engineered climate selection and other geoengineering approaches would follow this tradition rather than slowing human development in order to deal with the latest such problem in what some may regard as a more "natural" way.

B. *Legal Obstacles*

Attempts to use engineered climate selection or other geoengineering remedies to "solve" climate change problems might run into the problem that much of the western legal system assumes that there is no recovery for damages resulting from "acts of God." But if a person or government deliberately alters Earth's radiation balance or atmospheric GHG levels, even for a positive purpose, this may open up the possibility that those responsible could be sued for damages sustained due to climate-related events believed to be a result of their actions. The most obvious solution to this problem would be a change in the law to either deny recovery of damages from the use of such remedies or to make such liabilities fall onto governments, who would have to fund them out of taxes. This appears to be an area where legal inputs would be much needed if such remedies are to be actually used.

C. *Governmental Issues*

In a world of sovereign countries, an international process would need to be worked out to determine if, when, and how to deliberately alter global temperatures or GHG levels. This process would have to include processes for determining when results were unsatisfactory and how policy changes would be instituted to solve problems that might be encountered.[196] Although finding an acceptable process would not be without difficulty, it is hard to imagine that it would be more difficult than the negotiations that led to the Kyoto Protocol, and such a process would be needed if there are to be enforceable follow-on agreements, if such can even be accomplished. But once an agreement is reached, the actual implementation would not depend on the cooperation of many governments and people, as is the case under Kyoto and other governmental regulatory decarbonization approaches. Obviously it would matter not only which governmental organizations were selected to carry out geoengineering, but also how good a job they would do, since errors might well be costly. The main hope is that the organizations could be held accountable and would thereby have an incentive to do a good job. The alternative is to leave the outcome to nature, which is not accountable and which has no incentive to help humans.

D. *Strategic Difficulties*

Some scientists may oppose the geoengineering conclusions reached in this Article on the grounds that if global warming is "solved" through engineered climate selection or other geoeneering approaches, then it may be harder to persuade people to reduce fossil fuel use.[197] This raises the question of whether the goal is to solve environmental problems or to achieve some other objective. The position taken here is that the purpose should be to solve important environmental problems in the most effective and efficient way available.

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[196] For discussion of some of the alternatives for implementation, see Alan Carlin, *Implementation and Utilization of Geoengineering for Global Climate Change Control*, 7 SUSTAINABLE DEV. L. & POL'Y, Winter 2007, at 56, 56-58.

[197] *See* Ralph J. Cicerone et al., *Global Environmental Engineering*, 356 NATURE 472 (1992) (arguing that geoengineering solutions need to be taken more seriously); Crutzen, *supra* note 6, at 217 (discussing the importance of "[b]uilding trust between scientists and the general public"); Thomas C. Schelling, *The Economic Diplomacy of Geoengineering*, 33 CLIMATIC CHANGE 303, 303-07 (1996); Stephen H. Schneider, *Geoengineering: Could—or Should—We Do It?* 33 CLIMATIC CHANGE 291, 291-302 (1996).

Those who advocate a regulatory decarbonization-only approach risk achieving nothing, and thereby contributing to the risks facing our planet, in the hopes of achieving a different objective. It is better to separate the various problems—gradual global warming, ocean acidification, global warming tipping points, and global cooling from volcanic eruptions and nuclear conflicts—and design a realistic program to tackle each one. Otherwise, we risk everything on a single overall solution that appears unlikely to be achieved, and which cannot solve all of the problems anyway.

E. *Unintended Consequences*

An argument can be made that the earth's climate system is so complex and poorly understood that any attempt to directly manage it through geoengineering would risk unintended adverse consequences. Humans got themselves into their current situation because of the unintended consequences that resulted from their use of fossil fuels and other GHG-producing activities to increase human productivity and welfare. Decarbonization approaches also carry substantial risks that proponents almost never acknowledge—that they too may result in unintended consequences[198] and that they may not be effectively implemented and, as a result, the world will continue to warm, with all the adverse effects that have been discussed. But it is also conceivable that geoengineering would substantially solve the global climate change problem while creating other unintended consequences. Certainly, there is much that we do not yet understand about the climate system and how it would respond to various geoengineering efforts. But any approach would involve some amount of uncertainty, especially before serious research and testing is undertaken. History suggests that it is not until humanity is confronted with an immediate task and the need to learn enough to solve it that we normally come to understand all that we need to know about a particular subject.

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[198] *See, e.g.*, Eric A. Mazzi & Hadi Dowlatebadi, *Air Quality Impacts of Climate Mitigation: UK Policy and Passenger Vehicle Choice*, 41 ENVTL. SCI. TECH. 387, 387-92 (2007) (concluding that taxing vehicles according to CO_2 emission rates has resulted in a significant increase in consumer choice of small cars and diesel engines, which will have significant adverse health effects); s*ee also* Elisabeth Rosenthal, *Once a Dream Fuel, Palm Oil May Be an Eco-Nightmare*, N.Y. TIMES, Jan. 31, 2007, at C1 (describing rising demand for palm oil in Europe that has brought about the clearing of huge tracts of Southeast Asian rainforest by burning and the overuse of chemical fertilizer).

Although we cannot rule out the possibility of unintended consequences, this possibility can be minimized by a careful approach to testing and implementing proposed geoengineering solutions that take this possibility into account. For example, proposals can be tested on smaller scales before implementing them on a larger scale. This small-scale testing could ensure that changes were made or the project terminated outright if serious adverse effects are encountered. This is particularly needed when the effects of a large-scale approach are not easily reversed.

Fortunately, the leading engineered climate selection proposals do not appear to involve irreversibilities, and the effects appear to disappear in a relatively brief period. For example, in the case of stratospheric optimized particles, their effects could first be modeled further; if modeling did not reveal significant problems, we could follow with subscale, real world experiments, and could finally try the approach in a limited geographical area—such as the Arctic, which is experiencing the most rapid warming and has the lowest human population. If significant adverse effects were observed, they would dissipate within a year or two as particles gradually fell into the troposphere and were removed by normal atmospheric processes. In this circumstance, other types of particles could be tested or the project could be abandoned in the unlikely case that each type of suitable particle proves to result in critical, adverse, and unintended consequences. But pursuit of the decarbonization approaches currently proposed is very likely to result in continued global warming while the world waits for, and is likely to be disappointed by, the meager results.

One could also argue that not enough is known to justify using these relatively new geoengineering technologies. At the same time, little or no effort has been made to carry out the research and development[199] required to supply the information needed to use these technologies more effectively and efficiently. Given the promise of many of these technologies, the modest cost of the necessary research, the very large expenditures required for (and likely public dissatisfaction with) extensive GHG emission controls, and the possibly urgent need to reduce global warming, it is difficult to argue that the research should not be undertaken.

A recent editorial by a prominent member of the U.S. scientific establishment supports such research but also advocates a moratorium

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[199] *See supra* note 162 and accompanying text (noting the lack of research in geoengineering).

on any large-scale field experimentation.[200] Such a moratorium, however, is inconsistent with the urgency expressed by those concerned about global warming who advocate very large expenditures to control GHG emissions. It would appear premature to spend such sums on emissions control without first fully testing the alternatives.

CONCLUSION

As of late 2006, many environmentalists, some developed nations, and the state of California appear to have concluded that there is only one climate change problem—global warming—and only one solution—reducing greenhouse gas (GHG) emissions, usually through the Kyoto Protocol or similar regulatory decarbonization approaches. This Article has argued instead that there are actually four major, interrelated problems, and after a careful analysis of these problems and possible remedies for each of them, concluded that several different approaches will be required to solve all of them. Although some remedies can address certain climate change problems, none can address all of them. An effective and efficient climate change control program needs to use the best available approaches to solving each problem, instead of simply the single approach of reducing GHG emissions.

This Article has assumed that global climate change is a major environmental problem—perhaps the most difficult one that the world has ever faced. For the purposes of this Article, the climate change problem includes four related problems: continued and gradual global warming over the next few centuries; adverse effects unrelated to temperature of increasing levels of GHGs in the atmosphere; the potential effects of "tipping points" where warming may trigger particularly serious and abrupt adverse effects; and shorter-term episodes of global cooling caused by volcanic eruptions or nuclear conflicts. The Article then asked how effective and efficient a variety of management and technological approaches, particularly the Kyoto Protocol, would be in preventing or mitigating each of these problems, and whether there are alternative approaches that would be more so. The Article has taken a very broad view of the problem by including both long- and short-term impacts of human activities and natural forces on global temperatures and GHG levels. It is only by looking at all the

[200] Ralph J. Cicerone, *Geoengineering: Encouraging Research and Overseeing Implementation*, 77 CLIMATIC CHANGE 221, 221-26 (2006).

major aspects of the problem that effective and efficient solutions can be meaningfully discussed.

The Protocol and similar regulatory decarbonization approaches will not prevent either global warming or cooling, nor will they meet international goals for maximum temperature increases. If fully implemented, Kyoto would probably result in minor decreases in the temperature rise that would otherwise occur and would not provide any capability to respond to global cooling. One fundamental problem is that achieving the EU/UNFCC goals through a Kyoto-type approach would require the participation of most of the world's governments and population—including many rapidly growing countries that have not agreed to undertake any emission reductions—to restrict energy use in ways that would directly reduce their welfare, but the Protocol does not provide the effective incentives and penalties necessary to bring about such participation. It is difficult to see why politicians would adopt such unpopular and expensive constraints on their constituents' activities or why many of their constituents would not pursue every available loophole to avoid observing the imposed constraints.

It is unlikely that possible Kyoto follow-on agreements could overcome these implementation problems. In addition to being very difficult to implement, the Kyoto approach is probably economically inefficient and would have to be very expensive if it were to have a major impact on global temperatures. Additionally, it does not provide credit for the use of much less expensive engineered climate selection, and it is particularly illsuited for affecting global temperatures rapidly or flexibly. Trying to use it to rapidly decrease global warming would be even more expensive because of the need to replace GHG-emitting equipment early in the plan's life cycle. Pursuit of regulatory emissions reduction approaches is counterproductive, given their inherent implementation problems. Unfortunately, pursuing these approaches is likely to prevent serious consideration of more effective measures during the long period needed for the major deficiencies of this approach to become evident to all.

Given these very serious problems with the Kyoto approach, the Article then asked if there are superior management and technological alternatives for controlling climate change. To that end, Parts IV through V.E reviewed a wide array of control options using effectiveness, economic efficiency, and other relevant criteria. That analysis concludes that superior alternatives exist involving radiative forcing and that these alternatives would be technically sound; would allow continued growth of fossil fuel use; would very dramatically lower control costs; are economically efficient; would avoid the need for individual actions to reduce GHG emissions; and would permit relatively precise, rapid, and flexible adjustment of global temperatures. These alternatives, however, would not decrease any nontemperature-related adverse effects of GHGs, of which the most serious appears to be ocean acidification.

With this as background, Part V.F then extended the analysis to the four more detailed climate change problems:

(*P1*) *Gradually increasing global warming* could most rapidly, efficiently, and effectively be controlled using some of the more interesting radiative forcing or engineered climate selection remedies and result in significant adaptation expenses. As discussed, attempts to control this warming through GHG control under the Kyoto Protocol and similar approaches are likely to be very slow and largely unsuccessful. Other management approaches based on decentralized controls, voluntary actions, or liability for emissions would probably be even slower and less successful and efficient. However well intentioned and helpful they may be if they reduce emissions that are less expensive to control, there is also a danger that they will end up delaying effective action by providing false hope that these efforts will prove sufficient. Radiative forcing remedies, on the other hand, are some of the few realistic alternatives available to meet the current temperature goals. They could best be carried out on an internationally cooperative basis, but could also be done on a "go-it-alone" basis by technologically advanced countries, albeit at the risk of possible international condemnation.

(*P2*) *The nontemperature-related effects of increasing GHGs in the atmosphere* are both positive and negative. The major positive effect of high levels of carbon dioxide (increased plant growth) would be lost if atmospheric levels were returned to "normal." The most serious negative problem appears to be ocean acidification, but this problem is not well understood and deserves much further research before potentially very expensive remedies are undertaken. The principal choices for dealing with ocean acidification in particular appear to be: fertilizing the oceans with essential nutrients and minerals such as iron to promote the growth of carbon dioxide absorbing phytoplankton; using limestone to neutralize streams of newly generated carbon dioxide in advantageous circumstances; using carbon dioxide for enhanced oil recovery; sequestering carbon dioxide; and reducing atmospheric carbon dioxide emissions—in that order of decreasing attractiveness.

Fertilizing the oceans appears to be the lowest cost solution, but research is needed to make it possible for humans to emulate the more efficient approaches used by nature to export carbon onto the sea floor.

(*P3*) *Risks from "tipping points" or abrupt climate changes* would likely be reduced to the extent that atmospheric GHG levels and/or global temperatures were reduced. But if, as also appears likely, GHGs are not reduced to "normal" levels, the radiative-forcing remedies could be used to directly control global temperatures, thereby greatly reducing the adverse feedbacks and risks resulting from temperature rises. If imminent dangers should threaten, it furthermore appears feasible to use some radiative forcing remedies in a "rapid response" mode to greatly reduce these risks *if advance preparations are in place to do so.*

(*P4*) *Shorter-term episodes of global cooling from major volcanic eruptions* are a certain, and possibly even catastrophic, risk; *nuclear conflicts* may also occur with similar climatic consequences. Both can *only* be addressed through radiative forcing approaches. Advance preparations would again be required.

An effective and efficient solution would be to actively pursue a combination approach involving both engineered climate selection—radiative forcing by means of stratospheric particles optimized for this purpose—as well as a new effort to reduce ocean acidification. Immediate priority should be given to the former in order to quickly solve all the problems unrelated to ocean acidification, while the more difficult, much slower, and much more costly effort to reduce ocean acidification is undertaken. The cost of achieving the EU/UNFCCC temperature goals by the use of engineered climate selection would be modest and would not require any human lifestyle changes or adaptation to higher world temperatures (unless desired, of course). It appears to be the most effective and efficient first step toward global climate change control. This twofold approach could be used to rapidly reduce the risks stemming from adverse feedback/tipping point problems, from global warming, and from global cooling from major volcanic eruptions and nuclear conflicts. It could also be used to rapidly stabilize average global temperatures to any desired level. This should also allow time for a greatly expanded effort to better understand ocean acidification and to determine the extent to which ocean pH levels need to be raised and how this can be best achieved. Several suggestions have been made concerning geoengineering approaches, but it is clear that the problem deserves much greater attention and research.

Some aspects of the climate change problem could theoretically also be solved by GHG emission controls, although it is doubtful how effective they would be. If such emission controls were used, the place to start would appear to be to implement the lowest-cost options first, while delaying the more expensive ones until the problem is better understood. Such a delay would be economically rational, given the sensitivity of the costs of GHG emissions reductions to the rapidity with which they occur.

A significant effort would be required to fine-tune the proposals to implement engineered climate selection approaches, build an international mechanism for making decisions, and manufacture and transport the needed material and hardware. Notwithstanding this effort, this approach could be used to rapidly reduce the risks of adverse feedback or tipping point problems, to avoid significant adaptation expenses, and to rapidly stabilize global temperatures.

Some may object that not enough is known about these relatively new technologies to justify their immediate use. At the same time, however, little or no effort has been made to carry out the research and development necessary to reduce these risks. Given the promise of these technologies, the modest cost of the research, and the very large expenditures necessary for, and likely public dissatisfaction with, extensive GHG emission controls, it is difficult to understand why so little of this research and development has been undertaken.

This Article has reviewed several management approaches besides Kyoto and geoengineering projects, including voluntary efforts, non-Kyoto-based regulatory decarbonization, and a new approach involving the use of all available technologies and approaches. It finds that the voluntary, decentralized, and liability-based government-determined decarbonization approaches are likely to be even less effective and efficient than the Kyoto approach. Efforts to reduce GHG emissions on a less than national scale (as is being attempted in California) or even in a few countries, without equivalent actions by the rest of the world—particularly the most rapidly developing ones—cannot realistically achieve the temperature change limits adopted by the European Union and based on United Nations goals. Failure to achieve this goal is believed by proponents of GHG emission controls to pose "dangerous anthropogenic interference" with the climate system. Even a unified, worldwide effort to reduce GHG emissions to this extent, should it ever be undertaken, would be highly problematic because of the great dependence of modern society on energy use and the reluctance of most people to give up the advantages offered by modern society. The cost of achieving these goals by the use of engineered climate selection, however, would be comparatively modest and would not require any human lifestyle changes.

This Article therefore suggests a possible replacement for Kyoto, which would correct a number of the Protocol's deficiencies. If the world follows a Kyoto approach, this Article suggests a possible replacement for the Kyoto Protocol that would correct a number of the Protocol's deficiencies. But even in this case global temperatures appear almost certain to continue to increase, perhaps even at roughly current rates. At some point in the future this may become all too evident, and engineered climate selection may be more carefully considered. It would seem far better, however, not to wait until this happens before using engineered climate selection, since this would reduce the risk of hitting a tipping point, increase the possibility of warding off abrupt climate changes, provide protection from volcanic cooling or nuclear winters, and avoid various climate-induced unpleasantries and costly adaptation expenses in the meantime. Recently some have begun to advocate engineered climate selection as a fallback or insurance policy, in case their preferred regulatory decarbonization approach does not solve the problem or an unforeseen event occurs that requires a rapid response.[201] A more prudent and efficient strategy would appear to be to implement engieneered climate selection first and then see what further needs to be done.

Finally, this Article discussed five of the primary impediments to the use of engineered climate selection and other geoengineering approaches. Although these impediments are significant, they are easier to solve than the already evident problems surrounding the Kyoto approach.

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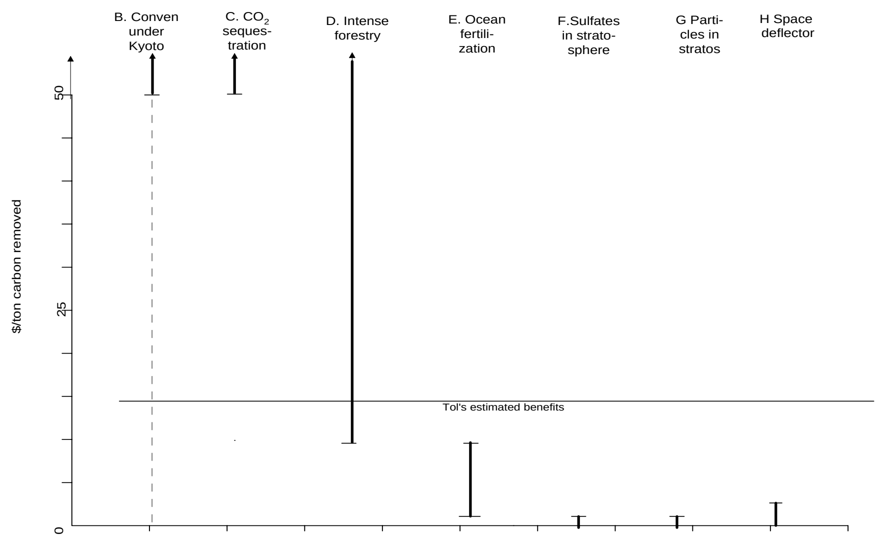
[201] *See* Crutzen, *supra* note 6.

APPENDIX

Figure 1: Costs and Benefits of Carbon Removal



Prepared by Alan Carlin based on Table 2 for costs and on Tol, *supra* note 128, for benefits. Marginal cost in U.S. dollars per ton carbon of CO_2 emissions mitigated for Column B. Other costs represent the range of estimated costs for categories of technology. There are believed to be some cases where the costs of Row B remedies are less than the marginal cost and even less than benefits.

Table 1: Usefulness of Selected Remedies in Solving Detailed Climate Change Problems

	***P1*: Gradual Global Warming**	***P2*: Ocean Acidification**	***P3*: Risks from "Tipping Points"**	***P4*: Short-term Cooling from Volcanic Eruptions/Nuclear Conflicts**	**Proposed Priority**
***B*: Conventional under Kyoto Protocol**	Effective if ever achieved, which is very unlikely; high cost; very slow results	If ever achieved (unlikely), would reduce but not eliminate problem; high cost	Vary with temperatures. Useless as a rapid response to imminent threats and to cooling	Useless	4
***C*: Artificial CO_2 sequestration/ neutralization**	Effective but high cost except possibly neutralization in ideal cases	Effective but high cost except some neutralization	Probably useless except for increasing temperatures by releasing concentrated CO_2	Unlikely to be useful, although where CO_2 is in concentrated form, it could *theoretically* be released with care	3
***E*: Ocean fertilization**	Probably effective if humans can learn how to employ it as efficiently as nature does; relatively low cost.	[Same as (P1)(E) cell.]	Can be started and stopped rapidly, but effects probably too gradual to be effective	Not applicable	2
***G*: Optimized particles in stratosphere**	Effective immediately; lowest cost	No effect	Can be quickly reduced with temperatures and also used for fairly rapid response	Effective as soon as particles are distributed unless there are interactions with volcanic emissions	1

The problem (*P*) numbers refer to those listed in Part I.B. The control options are identified by letters corresponding to the row numbers in Table 2 and the remedy (*R*) letters used in Parts IV and V. See Part V.G for an explanation of the proposed priorities.

Prepared by Alan Carlin based on Table 2 and text.

Table 1a: Cost-Effectiveness of Selected Remedies by Detailed Problem in Symbols

	P1: Gradual Global Warming	*P2*: Ocean Acidification	*P3*: Risks from "Tipping Points"	*P4*: Short-term Cooling from Volcanic Eruptions/ Nuclear Conflicts	Proposed Priority
***B*: Conventional under Kyoto Protocol**	X $ $ $ $	X $ $ $ $	*Long term:* X $ $ $ $ *Quick response:* NA	NA	4
***C*: Artificial CO_2 sequestration/ neutralization**	√√√√ $ $ $ $	√√√√ $ $ $ $	*Long term:* √√√√ $ $ $ $ *Quick response:* NA	Usually NA	3
***E*: Ocean fertilization**	√√√ $/10	√√√ $/10	Long term: √√√ $/10 *Quick response:* Limited	NA	2
***G*: Optimized particles in stratosphere**	√√√√ $/1000	NA	√√√√ $/1000	√√√√ $/1000	1

Explanation of symbols used:
X: Ineffective
√√√√: Highly effective
√√√: Probably effective if humans can learn to employ it as efficiently as nature does.
$: Marginal cost of about $100 per ton carbon or equivalent
$$$$: Marginal cost of about $400 per ton carbon or equivalent
$/10: Cost of about $10 per ton of carbon removed
$/1000: Cost of about 10 cents per ton carbon or equivalent
NA: Not applicable

Based on data in the corresponding rows of Table 2 but using the format of Table 1. Detailed estimates shown in Table 2 are used to approximate the effectiveness and cost of the remedies in an easier-to-understand form. See Parts V.G of the text for an explanation of the proposed priorities.
Prepared by Alan Carlin based on Table 2 and text.

Table 2: Evaluation of Some Alternative Detailed Remedies for Controlling Global Climate Change[202]

	***1*: Effective Environmental Outcome**	***2*: Dynamic Efficiency**	***3*: Cost Effectiveness**	***3a*: Cost of Control**[a]	***4*: Distributional Equity**
***R1/A*: No intentional climate change control (business as usual)**	Very low—depends on "dumb luck" to muddle through	Base case; not optimal due to high cost of climate change	No costs involved	NA[b]	Costs of warming may be greatest for those near sea level including low-lying LDCs
***R2/B*: Regulatory decarbonization using "conventional" technologies under the Kyoto Protocol**	Probably low given limited mitigation goals, short-term commitments, and limited incentives	Probably strongly negative since marginal costs are higher than climate change benefits of perhaps $15 per ton	Low compared to some technological approaches	50-400[ac] Estimated marginal cost to achieve EU/ UNFCCC goals	Only industrial countries face targets but LDCs help shape rules. LDCs receive some adaptation assistance
***C*: CO_2 artificial sequestration using injection underground or neutralization in oceans**	High if carried out on massive scale	Negative to strongly negative	Low	50-150;[d] 60-300[b] for CCS underground; 80-400[b] for ocean injection	Implementation costs borne by initiators; benefits and other possible costs borne by all
***D*: Intensive forestry to capture carbon in harvest-ed trees**	Low because of uncertainty about rate of accumulation	Likely to be negative but some projects could be positive	Low	10-100[d]	Implementation costs borne by initiators; benefits and other possible costs borne by all
***E*: Ocean fertilization with phosphate/ iron**	Probably high if humans can be as effective as nature is	Probably high	High—but not the highest	1-10[d]	Implementation costs borne by initiators; benefits and other possible costs borne by all

[202] *See supra* Part V.

Table 2: Evaluation of Some Alternative Detailed Remedies for Controlling Global Climate Change

5: Flexibility	*5a:* Alter Pace	*5b*: Global Cooling	*5c*: Temp. Redistribution	*6*: Participation & Compliance	*7*: Other Environmental Risks	*8*: Additional Considerations
Little desired or likely	NA	NA	NA	None needed	None	Included as base case
Emission ceilings locked in but only for 5 years; climate response very slow	Possible but very difficult	No	No	Incentives very weak; requires massive international cooperation & bureaucratic effort;	None known	Protocol already in place calling for reductions by some countries; reductions in oil use increases national security
Could be halted rapidly, but increase in pace could only be done slowly	Yes	Not likely but possible to remove CO_2 if concentrated	No	International cooperation desirable for siting purposes	Probably low risk except for ocean injection, which could contribute to ocean acidification. Potential leakage problems for underground	Some experience with old oil and gas fields; possible NIMBY problems elsewhere
Almost no flexibility because of time required to stop, start, or harvest trees	Only very slowly	Could remove trees and burn them	No	Cooperation and approval of landowners and probably governments required	Low risk; intensive cultivation will impact soils and biodiversity	Political issues: who pays costs?; whose land is used?
Medium to control warming but difficult to reduce nutrient flow	Yes	No	No	International cooperation desirable	May be some risks due to many unknowns at large scales	Possible liability and other legal concerns; increased productivity of ocean food chain

Table 2 (cont.)

	***1*: Effective Environmental Outcome**	***2*: Dynamic Efficiency**	***3*: Cost Effectiveness**	***3a*: Cost of Control[a]**	***4*: Distributional Equity**
***F*: Sulfur-containing particles added to stratosphere to control global warming**	Very high; proven by major volcanic eruptions; no ocean acidification mitigation	Strongly positive; CO_2 increases would also aid agriculture	Very high for cooling purposes	<<1[d]	Probably fairer;[e] implementation costs borne by initiators; benefits and other possible costs borne by all
***G*: Optimized radiative forcing by injecting specialized substances in stratosphere, e.g., *see supra* note 124**	Very high based on (*F*) but unproven in real world trials; no ocean acidification mitigation	Strongly positive for warming; Other benefits, e.g., UV protection, plant growth, offset volcanic eruption	Very high for both heating and cooling	<<1[f], or, at the risk of trying to be too precise, 0.02 to 0.1[g]	Probably fairer;[e] implementation costs borne by initiators; benefits and other possible costs received/ borne by all
***H*: Optimized radiative forcing by building flexible deflector in space between Earth and Sun as specified in *supra* note 125**	High but no experience with building anything so large so far from Earth; no ocean acidification mitigation	Appears to be high for warming; other benefits, e.g., UV protection, plant growth, offset volcanic eruption	High for both heating and cooling unless cost is very high	0.2-2[f] (costs much less certain here, and probably underestimated—see text)	Probably fairer;[e] implementation costs borne by initiators; benefits and other possible costs received/ borne by all

Prepared by Alan Carlin based on alternatives analyzed by Lasky[c] (Remedy *B*), Keith 2000[d] (Remedies *C, D, E*, and *F*), IPCC[h] (*E*), NAS 1992[j] (*F*), Keith 2001[f] (*G* and *H*), Michaelson[e] (Columns 1, 4, & 6), and Teller et al. 1997, 1999, and 2002, and 2004[i] (*F, G*, and *H*).

Footnotes for Table 2:

[a] Marginal cost in U.S. dollars per ton carbon of CO_2 emissions (or equivalent) mitigated for Row B only. Other costs in this column represent the range of estimated costs for categories of technology. There will be some cases where the costs of Row B remedies are a lot less than the marginal cost.

[b] Does not apply; since none are mitigated, there is no cost of mitigation.

[c] *See* Lasky, *supra* note 129 and accompanying text.

Table 2 (cont.)

5: Flexibility	*5a:* Alter Pace	*5b*: Global Cooling	*5c*: Temp. Redistribution	*6*: Participation & Compliance	*7*: Other Environmental Risks	*8*: Additional Considerations
High at least to control warming. Changes depend on residence time in stratosphere	Intensify rapidly; 5 year lag to decrease intensity	Not without changing substance used	Possible but only to cool	Not required once remedy agreed on	Medium–possible adverse interactions with other stratospheric species; no reduction in ocean acidification	Possible liability if courts should decide that disasters have resulted
High for both warming and cooling. Good chance for controlling abrupt climatic changes, as from volcanic eruption	Intensify rapidly; 5 year lag to decrease intensity	Yes by changing substances used	Possible by varying application by latitude	Not required once remedy agreed on	Probably low risk but needs careful research, particularly on impact on stratospheric chemistry. Ocean acidification not addressed	Could reduce adverse effects of solar radiation on earth. Possible liability problem.
Extremely high for both warming and cooling; best chance for controlling abrupt climatic changes as from volcanic eruption	Intensify almost immediately by adjusting deflector	Yes by changing deflector placement	Not clear from available info; research required	Not required once remedy agreed on	Probably even lower risk than G but still needs careful research; quickly reversible if unforeseen problems. Ocean acidification not addressed.	Possible liability problem

[d] *See* Keith, *supra* note 17.

[e] *See* Michaelson, *supra* note 18.

[f] *See* Keith, *supra* note 156.

[g] This range of estimates assumes an estimated cost of $0.2 to $1.0 billion per year, Teller, Active Climate Stabilization, *supra* note 119, and an assumed offset of approximately 10 gigatons of carbon per year. The cost estimates assume that various types of particles are carried into the stratosphere using a fleet of six high-altitude cargo planes. Ten gigatons is representative of the carbon emission reduction needed to achieve a 450 ppmv CO_2 level in the atmosphere compared to projected IS92a emissions in 2060.

[h] *See* IPCC *supra* note 113; based on Table SPM.5 with dollar values for capture from new large-scale power plants with dollars per ton CO_2 converted to dollars per ton carbon.

[i] *See* Teller, *Active Climate Stabilization*, *supra* note 119.

[j] *See generally* souces by Teller, *supra* note 18.