Statement before the House Committee on Science and Technology

"Researching Solar Radiation Management as a Climate Policy Option"

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1 Introduction

1.1 Summary

Chairman Gordon, ranking member Hall, other members of the Committee, thank you for the opportunity to appear before you today. I am Lee Lane, a Resident Fellow at the American Enterprise Institute, where I am also co-director of AEI's geoengineering project. AEI is a non-partisan, non-profit organization conducting research and education on public policy issues. AEI does not adopt organizational positions on the issues that it studies, and the views that I express here are solely my own.

The Committee is to be commended for its decision to address the issue of geoengineering as a possible response to climate change. Climate change is an extremely difficult issue. It poses multiple threats that are likely to evolve over time. Too often, climate policy discussions have been locked into an excessively narrow range of possible responses.

My statement this morning urges that the committee treat this hearing as a first step in what should grow into a serious, sustained, and systematic effort by the U.S. government to conduct research and development (R&D) on solar radiation management (SRM). SRM, as the committee has heard, envisions offsetting man-made global warming by slightly raising the amount of sunlight that the Earth reflects back into space.

In a recent study, a panel of five highly acclaimed economists, including three Nobel laureates, rated fifteen possible concepts for coping with climate change. The rankings were based on the panel's assessments of the ratio of benefits to costs of each approach. Research on the two SRM technologies discussed below ranked first and third among these concepts. The expert panel was aware that many doubts continue to surround SRM, but its members were also clearly impressed with SRM's vast potential as one tool among several for holding down the cost of climate change.

Research into SRM is needed in part because, for many nations, a steep decline in greenhouse gas (GHG) emissions may well cost more than the perceived value of its benefits (Nordhaus, 2008; Tol, 2009; Posner and Sunstein, 2008). The record of the last twenty years of climate negotiations amply demonstrates that steep emission reductions are unlikely, and will probably remain so for a long time to come. Yet, without such controls, and even with them, some risk exists that quite harmful climate change might occur.

A successful SRM system could greatly reduce the risk of these harmful effects. SRM, it is true, carries some risks of its own. An R&D program may, however, provide additional information with which to assess these risks and, perhaps, to devise means to limit them. The potential net benefits of SRM are very large indeed. One recent study found that the difference between the costs of deploying SRM and the savings it could reap amount to $200 billion to $700 billion (Bickel and Lane, 2009). The costs of an R&D effort appear to be minuscule compared with these possible gains.

1.2 Main SRM concepts

SRM aims to offset the warming caused by the build-up of man-made greenhouse gases in the atmosphere by reducing the amount of solar energy absorbed by the Earth. GHGs in the atmosphere absorb long-wave radiation (thermal infrared or heat) and then radiate it in all directions—including a fraction back to Earth's surface, raising global temperature. SRM does not attack the higher GHG concentrations. Rather, it seeks to reflect into space a small part of the sun's incoming short-wave radiation. In this way, temperatures are lowered even though GHG levels are elevated. At least some of the risks of global warming can thereby be counteracted (Lenton and Vaughan, 2009).

Reflecting into space only one to two percent of the sunlight that strikes the Earth would cool the planet by an amount roughly equal to the warming that is likely from doubling the pre-industrial levels of greenhouse gases (Lenton and Vaughan, 2009). Scattering this amount of sunlight appears to be possible.

Several SRM concepts have been proposed. They differ importantly in the extent of their promise and in the range of their possible use. At least two such concepts appear to be promising at a global scale: marine cloud whitening and stratospheric aerosols.

1.2.1 Marine Cloud Whitening

One current proposal envisions producing an extremely fine mist of seawater droplets. These droplets would be lofted upwards and would form a moist sea salt aerosol. The particles within the aerosol would be less than one micron in diameter. These particles would provide sites for cloud droplets to form within the marine cloud layer. The up-lofted droplets would add to the effects of natural sea salt and other small particles, which are called, collectively, cloud condensation nuclei (Latham *et al.*, 2008). The basic concept was succinctly described by one of its developers:

> "Wind-driven spray vessels will sail back and forth perpendicular to the local prevailing wind and release micron-sized drops of seawater into the turbulent boundary layer beneath marine stratocumulus clouds. The combination of wind and vessel movements will treat a large area of sky. When residues left after drop evaporation reach cloud level they will provide many new cloud condensation nuclei giving more but smaller drops and so will increase the cloud albedo to reflect solar energy back out to space." (Salter *et al.*, 2008)

The long, white clouds that form in the trails of exhaust from ship engines illustrate this concept. Sulfates in the ships' fuel provide extra condensation nuclei for clouds. Satellite images provide clear evidence that these emissions brighten the clouds along the ships' wakes.

Currently, the widely discussed option for implementing this approach envisions an innovative integration of several advanced technologies. The system calls for wind-powered, remotely controlled ships (Salter *et al.,* 2008). However, other more conventional deployment systems may also be possible (Royal Society, 2009).

Analyses using the general circulation model of the Hadley Center of the UK Meteorological Office suggest that the marine clouds of the type considered by this approach contribute to cooling. They show that augmenting this effect could, in theory, cool the planet enough to offset the warming caused by doubling atmospheric GHG levels. A relatively low percentage of the total marine cloud cover would have to be enhanced in order to achieve the desired result. A British effort is developing hardware with which to test the feasibility of this concept (Bower *et al.*, 2006).

1.2.2 Stratospheric Aerosols

Inserting aerosols into the stratosphere is another approach. The record of several volcanic eruptions offers a close and suggestive analogy. The global cooling from the large Pinatubo eruption (about .5 degrees Celsius) that occurred in 1991 was especially well-documented (Robock and Mao, 1995). Such eruptions loft particles into the atmosphere. There, the particles scatter back into space some of the sunlight that would otherwise have warmed the surface. As more sunlight is scattered, the planet cools.

Injecting sub-micron-sized particles into the stratosphere might mimic the cooling effects of these natural experiments. Compared to volcanic ash, the particles would be much smaller in size. Particle size is important because small particles appear to be the most effective form for climate engineering (Lenton and Vaughan, 2009). Eventually, the particles would descend into the lower atmosphere. Once there, they would precipitate out. "The total mass of such particles would amount to the equivalent of a few percent of today's sulfur emissions from power plants" (Lane *et al.*, 2007). If adverse effects appeared, most of these effects would be expected to dissipate once the particles were removed from the stratosphere.

Sulfur dioxide (SO_2), as a precursor of sulfate aerosols, is a widely discussed candidate for the material to be injected. Other candidates include hydrogen sulfide (H_2S) and soot (Crutzen, 2006). A fairly broad range of materials might be used as stratospheric scatterers (Caldeira and Wood, 2008). It might also be possible to develop engineered particles. Such particles might improve on the reflective properties and residence times now envisioned (Teller *et al.*, 2003).

The volumes of material needed annually do not appear to be prohibitively large. One estimate is that, with appropriately sized particles, material with a combined volume of about 800,000 m^3 would be sufficient. This volume roughly corresponds to that of a cube of material of only about 90 meters on a side (Lane *et al.*, 2007). The use of engineered particles could, in comparison with the use of sulfate aerosols, potentially reduce the mass of the particles by orders of magnitude (Teller *et al.*, 2003).

Several proposed delivery techniques may be feasible (NAS, 1992). The choice of the delivery system may depend on the intended purpose of the SRM program. In one concept, SRM could be deployed primarily to cool the Arctic. With an Arctic deployment, large cargo planes or aerial tankers would be an adequate delivery system (Caldeira and Wood, pers. comm., 2009). A global system would require particles to be injected at higher altitudes. Fighter aircraft, or planes resembling them, seem like plausible candidates. Another option entails combining fighter aircraft and aerial tankers, and some thought has been given to balloons (Robock *et al.*, 2009).

1.3 Air capture of CO_2 (AC)

Air capture (AC) of carbon dioxide (CO_2) is the second family of climate engineering concepts. AC focuses on removing CO_2 from the atmosphere and securing it in land- or sea-based sinks.

> "Air capture may be viewed as a hybrid of two related mitigation technologies. Like carbon sequestration in ecosystems, air capture removes CO_2 from the atmosphere, but it is based on large-scale industrial processes rather than on changes in land use, and it offers the possibility of near-permanent sequestration of carbon." (Keith *et al.*, 2005)

Like carbon capture and storage (CCS), air capture involves long-term storage of CO_2, but air capture removes the CO_2 directly from the atmosphere rather than from the exhaust streams of power plants and other stationary sources (Bickel and Lane, 2009).

Were technological progress to greatly lower the costs of AC, this approach might offer a number of advantages. However, even with costs far below those that are now possible, large-scale AC appears to face huge cost penalties vis-à-vis SRM. For instance, compare the cost of using AC to achieve the cooling possible with one W m^{-2} of SRM. The present value cost of achieving this goal (over a 200-year period) with AC is (very optimistically) $5.6 trillion. The direct cost of SRM might well be less than $0.5 trillion (Bickel and Lane, 2009).

Proponents of AC may argue that even this low level of SRM might entail some costs from unwanted side effects. AC, they may also note, conveys some added benefits with regard to ocean acidification. These points are well-taken; yet it is far from clear that, when taken together, these benefits would be worth anything even remotely near $5 trillion. It seems safe to conclude that, compared with SRM, when economics is accounted for, AC should be a distinctly lower priority target for R&D. Thus, the rest of my remarks this morning will focus on SRM.

2 Deploying SRM might yield large net benefits

2.1 Initial estimates of benefits and direct costs

Expert opinion suggests that SRM is very likely to be a feasible and effective means of cooling the planet (Royal Society, 2009). Indeed, this concept may have more upside potential than does any other climate policy option. At the same time, SRM, like all other options, entails risks, and these will be discussed below.

As noted earlier, recent study found that the benefits of SRM exceeded the costs of operating the system by an amount that would translate into $200 billion to $700 billion *per year* (Bickel and Lane, 2009). Some of these benefits stem from lowering the economic harm expected from climate change. SRM, by lowering the risk of rapid climate change, would also allow a more gradual path toward GHG control – lowering the total costs of controls.

It is quite true that these benefit estimates are preliminary and subject to many limitations. They do not, for instance, account for the indirect costs implied by possible unwanted side effects of SRM. These indirect costs could be substantial, and the next section of my statement will discuss them. At the same time, the estimate excludes several factors that would be likely to increase the estimated benefits.

2.2 Abrupt climate change might increase the value of SRM

For example, some grounds exist for fearing that many of the current models understate the risks of extremely harmful climate change (Weitzman, 2008). Emission controls, even if they could be implemented effectively, *i.e.* globally, require more than a century before actually cooling the planet (IPCC, 2007). SRM, however, might stand a much better chance of preventing the worst should such a nightmare scenario begin to unfold. Once developed, either of the two techniques discussed above could be deployed very rapidly. The low costs of SRM mean that a few nations working together, or even a single advanced state, could act to halt warming, and it could do so quickly (Barrett, 2009).

Merely developing the capacity to deploy SRM, therefore, is like providing society with a climate change parachute. And like a real parachute, having it may be valuable even if it is not actually deployed. In general, the more one credits the risk of rapid, highly destructive climate change, the greater is the potential value of SRM.

2.3 Suboptimal controls will raise the value of SRM

Less-than-optimal GHG emission controls, or no controls, would decrease global economic welfare, but these flawed policies would actually increase the positive contribution of SRM. This fact is important because actual GHG controls are certain to be far from the broad, uniform, price-based incentives that economic analysis calls for. In fact, few, if any, countries are likely to implement controls of this kind (Lane and Montgomery, 2009).

Excess GHG emissions are an example of a fairly common kind of market failure, which can arise when property rights allow open access to a valuable resource. Instances include open access to grazing land, fishing grounds, or to oil and gas reservoirs. Open access can cause under-investment in maintaining the resource and too much consumption of it (Eggertsson, 2003). In the case of climate, the open access resource is the atmosphere's capacity to absorb GHG discharges.

In principle, collective action could solve the problem by limiting access. In practice, efforts to limit open access property rights often founder. For example, wild ocean fish stocks are being seriously depleted. Curbs on the over-pumping of oil and gas resources have sometimes worked, but often they have only done so after a great deal of economic waste had already occurred (Libecap, 2008). So far, GHG control has been another instance of this pattern of frequent failure.

Further, GHG control has many of the features that make an effective global solution more difficult to attain. In such transactions, the more diverse are the interests of the parties, the poorer are the prospects for success (Libecap, 2008). Contrasting value judgments often cause conflict (Alston and Mueller, 2008). With GHG controls, the differing interests of richer and poorer nations have emerged as especially problematic (Bial *et al*., 2001).

Thus, for China and India, economic development offers better protection from harmful climate change than do GHG limits. This choice makes sense. Industrialization can boost the ability to adapt to climate change. Of course, it can also relieve many other more acute problems. For these countries, slowing growth in the name of GHG control may simply be a bad investment (Schelling, 2002). To put the matter bluntly, for China and India, there seem to be good reasons for thinking that taking any but the lowest cost steps to control GHG emissions is just not worth the cost.

As a result, China and India have largely limited their GHG control steps to those that in the U.S. context have been called "no regrets" measures. These are steps that would make sense absent concern about climate change. Such measures will have at best marginal impacts on the growth of emissions. Yet unless far steeper GHG cuts are implemented, widely cited goals for 2050 and 2100 are simply unattainable (Jacoby *et al*., 2008).

The most logical inference from this situation is that those goals will not, in fact, be met. If they are not, climate change damages will exceed those projected to occur with an optimal control regime, as will the risks of abrupt, high-impact climate change. This prospect suggests that SRM is likely to be more valuable than the recent Bickel/Lane analysis indicates.

3 Important uncertainties remain

SRM could, then, offer important help in reducing some of the risks of climate change, but it poses some risks as well.

3.1 Concerns about possible indirect costs

Some of the risks that have been ascribed to SRM are somewhat poorly defined (Smith, 2009). Others, however, are clear enough, at least in concept. One such risk is the possible lessening of rainfall. The strength of the Indian or African monsoons is a particular worry. Other concerns also exist. For example, until chlorine concentrations return to levels present in the 1980s, sulfate aerosols added to the stratosphere may retard the ozone layer's recovery (Tilmes *et al.*, 2008).

Concerns have also arisen over acid precipitation if SO_2 were injected into the stratosphere. In addition, stratospheric aerosol injections would whiten skies, interfere with terrestrial astronomy, and reduce the efficiency of some kinds of solar power (Robock, 2008). Finally, some analysis suggests the possibility of "rebound warming" should SRM be deployed for a long time period and then halted abruptly (Goes *et al.*, 2009).

3.2 Viewing indirect costs in a larger perspective

Several points about the above concerns warrant attention.

None of the possible ill-effects of SRM has been monetized. Therefore, how they compare with SRM's apparently large potential benefits is unclear. In fact, the scale of the effects of these unintended consequences is highly speculative. With regard to the Indian monsoon, for example, the underlying climate science is too uncertain to assess the scale of the changes with confidence (Zickfeld *et al.*, 2005). Thus, Rasch *et al.* (2008), on which Robock is an author, observe:

> "Robock *et al*. (2008) have emphasised that the perturbations that remain in the monsoon regions after geoengineering are considerable and expressed concern that these perturbations would influence the lives of billions of people. This would certainly be true. However, it is important to keep in mind that: (i) the perturbations after geoengineering are smaller than those without geoengineering; (ii) the remaining perturbations are less than or equal to 0.5 mm d^{-1} in an area where seasonal precipitation rates reach 6–15 mm d^{-1}; (iii) the signals differ between the NCAR and Rutgers simulations in these regions; and (iv) monsoons are a *notoriously* difficult phenomenon to model [Annamalai *et al.*, 2007] [emphasis in original].

Ozone depletion may be a problem, but it is likely to grow less severe with the passage of time. Acid deposition seems to be a considerably less serious problem, as a recent study concluded that "…the additional sulfate deposition that would result from geoengineering will not be sufficient to negatively impact most ecosystems, even under the assumption that all deposited sulfate will be in the form of sulfuric acid" (Kravitz *et al.*, 2009).

On rebound warming, the significance of the problem is, again, unclear. For the effect to be large, the SRM regime would have to remain in place for at least several decades. Also, during this period, adaptation and GHG control efforts would have to be held to low levels (Bickel and Lane, 2009). *Ex ante*, such a course of events may be possible, but it hardly seems inevitable or, perhaps, even likely.

All of these concerns may warrant study. Nonetheless, to take a step back from the details, a few broader factors should also be kept in mind. *Most importantly, it is worth noting that the relevant choice before us is not between a climate-engineered world and a world without climate change; rather, it is between the former and the world that would prevail without climate engineering.* SRM may, indeed, do some harm. Society may, however, have to choose between accepting this harm on the one hand and running the risk of a planetary emergency on the other (Bickel and Lane 2009).

Finally, in assessing SRM, it is important to keep in mind that all climate policy options entail side-effects. GHG controls, for instance, may imply greater reliance on biofuels or nuclear power. Border tax adjustments may unleash a global trade war (Barrett, 2007). In weighing the relative priority of SRM and GHG control, these factors are no less relevant than SRM's impacts on rainfall or ozone. The key to climate policy is finding the mix of responses that minimizes total costs more than it is about either/or choices.

4 Approaches to limiting the risks of SRM

Since the risks of unintended consequences are the major barriers preventing the exploitation of this option, it is important to find means of lowering those risks. A number of options might serve this purpose.

4.1 R&D as a risk reduction strategy

Currently, we lack much of the information that would be needed to weigh all of the potential risks of SRM against its possible benefits. Only an R&D program can buy this information, and the potential benefits of SRM appear to be very large compared to the costs of such an R&D effort. A vigorous, but careful, R&D program may offer the means of reducing the risks of SRM. It may identify faulty concepts and find new means of avoiding risks. Progress in climate science can also increase the expected benefits of SRM (Goes *et al.*, 2009).

Such an R&D program would begin with modeling and paper studies, move to laboratory testing, and eventually embark on field trials. The latter would start small and increase in scale by increments. As R&D progresses, spending would increase from tens of millions of dollars in early years to the low billions of dollars later. Total spending may fall in the range of $10-15 billion (Bickel and Lane, 2009). The work would stress defensive research *i.e*. research designed to identify and limit possible risks. A recent report has defined this type of research agenda for stratospheric aerosols (Blackstock *et al.*, 2009).

Research cannot entirely eliminate risk (Smith, 2009). Yet the risk of deploying a system under emergency conditions and without full testing are likely greatly to exceed those entailed by deploying a more fully tried and better understood system. Again, none of the options for dealing with climate change is free of risk.

4.2 Delayed deployment as a risk management strategy

The passing of time seems likely to diminish the risks of deploying SRM. One option, therefore, might be to delay deployment. This approach offers two advantages.

First, delay is likely to make it easier for the nations wishing to deploy SRM to gain international acquiescence for their plans. Today, some nations may still benefit from additional warming. Such states might strenuously object to near-term efforts to halt warming. Russia, one of the nations that might adopt this view, is a great power. It could probably apply enough pressure to prevent any other nation from deploying SRM. However, as decades pass, climate change is increasingly likely to threaten even Russia with net costs. As this happens, Russian and other objections to SRM are also likely to fade.

Second, the ozone depletion problem will also diminish with time. The stock of ozone-depleting chemicals in the atmosphere is shrinking. Before mid-century, levels will return to those that prevailed pre-1980. At that point, the impact of stratospheric aerosols on UV radiation also loses significance (Wigley, 2006).

Delayed deployment, of course, would also lower the difference between SRM's total benefits and its direct costs. Even so, large net benefits remain. This result obtains for both SRM concepts. Thus, if marine cloud whitening were deployed in 2055, the estimated present discounted value of the benefits exceeds that of the direct costs by at least $3.9 trillion, and perhaps by as much as $9.5 trillion (in 2005 dollars). If stratospheric aerosols were deployed in 2055, the gap between total benefits and total costs would range between $3.8 trillion and $9.3 trillion (Bickel and Lane, 2009).

5 Proposals for international governance require caution

For some people, creating an international governance regime is the preferred choice for controlling the risks of SRM. A number of proposals for establishing systems of international governance of SRM seem suddenly to have sprouted up. Many of them seem to be couched in somewhat alarming tones about future conflicts, and most seem to be accompanied by expressions of great urgency (Victor *et al.*, 2009). In responding to them, caution is in order.

5.1 Proposals for regulation require balancing of risks

To start with, it is important to recognize that a regime of controls can and often does produce counter-productive results. An overly restrictive system can raise the costs of undertaking R&D. Higher costs may narrow the field of active researchers. Since competition spurs technological progress, a regulatory regime that adds to research costs may slow the pace of progress (Arrow, 1962; Cohen and Noll, 1991; NRC 1999; Sarewitz and Cohen, 2009). If so, lowering the risks of unintended harm from SRM might be purchased at the costs of higher risks from abrupt, high-impact climate change. This trade-off may be worthwhile, or it may not be, depending on how one rates the relative risks.

5.2 U.S. interests may differ from those of other states

A second caution pertains to nations' different weights in world politics. A few nations command much more heft than do others. The U.S., China, and Russia are clearly in this category; others may be in the process of joining it. These states have a disproportionate ability either to carry an SRM regime into effect or to impede another state from doing so. If any of these states were to conclude that SRM was necessary to protect its vital interests, a system of international restraints would be most unlikely to constrain them.

For the U.S., the question of whether to foster the development of an international body with the authority to regulate SRM entails accepting possible future constraints on its own freedom of action, as well as constraints on other states that might be acting in accord with U.S. preferences. In exchange, the U.S. would gain possible added support were it is seeking to halt or change SRM activity by another power.

In considering this trade-off, it may be worth pondering that at least two other great powers, China and Russia, are autocracies. It is at least possible that these states are far less constrained by global public opinion than is the United States. In this case, in consenting to the creation of a global regime for governing SRM, the U.S. might be accepting a more binding limit on its own actions than that which it gains on the actions of the other great powers.

5.3 Who should consider SRM regulation?

SRM regulation is a matter of U.S. foreign policy. In this matter, U.S. interests may be congruent with those of some countries and clash with those of others. In addition to distinctions in wealth, power, and climate, states may differ in risk averseness. The strength of the contrasting U.S. and EU reactions to genetically modified organisms suggest that in at least some specific instances, such differences may be large.

Technical and scientific expertise is certainly important to the issue of how (or whether) SRM should be subject to international control. Yet the more basic question lies in the definition of national interests. This question is not technical; it is political. And how it is answered may well affect any nation's choices among international control regimes. For this reason, recommendations made by panels of scientists or lawyers may miss central aspects of the issues and yield misleading results. Such advice may still provide useful insights, but it should be handled with care.

6 SRM as part of a broader context

6.1 Multiple responses are needed to cope with climate change

Multiple tools are available for coping with climate change. Adaptation to change is likely to be the primary response for many decades. Weak and patchy greenhouse gas (GHG) controls are in place, but these measures fall far, far short of those that would be needed to actually halt climate change. And they are likely to continue to do so. Solar radiation management (SRM) offers great upside potential.

Still, it remains in the concept stage and is surrounded by uncertainties. Eventually, even air capture of CO_2 may become appealing, although its economic feasibility remains speculative.

In any case, a mix of climate policies is better than placing too much stress on any one response. GHG emissions pose multiple threats, and multiple responses are likely needed to respond to them. Further, at some point all responses are likely to encounter diminishing marginal returns. Excessive reliance on any one policy option is likely to raise net costs.

6.2 New knowledge as a key to climate policy success

With the current state of science and technology, the costs of coping with climate change are likely to be high. New knowledge may, however, drastically lower those costs. As just discussed, R&D on SRM may allow a better assessment of this option as well as offer ways of limiting its risks and controlling its costs. Better climate science is likely to enable more cost-effective adaption to climate change. R&D on new energy sources or on capturing and storing CO_2 might lower the cost and raise the political acceptability of GHG controls. Each of the six climate policy options selected by the above-mentioned economists' panel as being the most promising centered on the search for one or another form of new knowledge. Clearly, in the economists' opinions, research is a powerful strategy for dealing with climate change.

The quest for new knowledge may not, though, be easy. First, its results are inherently uncertain. Diversified risks and hedging are important. Second, research can take time. Electrification of the global economy, for example, has been going on for over a century and is still far from complete. Third, the right kind of rules and structures can make the difference between success and failure. This Committee is very well positioned to raise questions about the kinds of arrangements likely to maximize the chances of R&D success. I hope that this hearing may prove to be an important step forward in that inquiry.

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