Earth and Climate Systems Engineering

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It is a pleasure to be back in this auditorium to address a topic of surpassing importance and complexity representing an incomparable challenge to engineering and technology. Earth Systems Engineering (ESE) in the case of climate, Climate Systems Engineering (CSE), encounters a problem of intense national and international interest. The past decade has seen threatening projections of future climate conditions and the resulting environmental, economic and social consequences.

It is important to understand what we mean when we consider Climate Systems Engineering. Humanity has been engineering earth systems for thousands of years and we live in an earth-engineered system. Primitive engineering was aimed at local or regional issues such as engineering for shelter, for water resources, for transportation, to cope with the vicissitudes of climate. Today engineering and technology are ubiquitous in achieving understanding, projecting the future, mitigating and adapting to climate changes. No branch of engineering and technology is immune today from involvement in climate systems engineering, not communications, computers, biotechnology, or space technology in addition to more traditional disciplines.

In earlier times, engineering was undertaken without regard to ancillary and frequently deleterious consequences. The need to address these consequences has in recent years penetrated our consciousness and with it the concept of Earth Systems Engineering. The concept implies the consideration of the human dimensions of climate change – the environmental, ecological, social and economic ramifications. Climate Systems Engineering is a multi-purpose, multi-disciplinary activity which seeks to anticipate consequences.

Climate change is the archetypical global phenomenon lending itself to Earth Systems Engineering approaches. The nations of the world are seeking action to forestall the adverse effects of projected climate warming through engineering and technology. Until recent years, changes in climate have been regarded as acts of God to which one could only hope to adapt. Today, however, climate change is in part an act of humanity. Engineering is now central to our understanding of the causes of climate change, its monitoring and mitigation, as well as in its traditional role of enabling the adaptation to climate change.

Engineering and Understanding

It is fair to say that without engineering and technology we would not today understand the causes, be able to project the future and take steps to mitigate or adapt to the vagaries of climate variations. Engineering and technology now represent the underpinnings of modern weather and climate science. Scientific weather forecasting became possible 150 years ago with the introduction of the telegraph of Samuel B. Morse. The telegraph permitted the transmission of weather conditions from remote to central locations for analysis. It is only since World War II, 60 years ago, that we have seen previously unimagined progress. Radiosondes have given us a view of the upper atmosphere; radar has transformed our understanding of the dynamics of precipitation and cloud systems; computers have enabled the mathematical modeling of weather and climate that transform prediction from art to science; and space technology has permitted the global imaging, sounding and location capabilities to provide global monitoring of weather and climate. These engineering achievements have been the keys to the modeling of the ocean, atmosphere, hydrologic and land surface systems and have enabled the understanding and prediction of climatic conditions that have given rise to the international concerns about the consequences.

The State of Knowledge

It is not the purpose today to discuss climate science in any depth. But without some sense of causes and expectations, the concept of Climate Systems Engineering is meaningless. Briefly, the increasing global use of fossil fuels, deforestation and emissions from other sources as population has burgeoned, has caused an increase in the atmospheric concentration of greenhouse gases since the beginning of the industrial age. From vanishingly small amounts of CO_2 emissions in 1860 to over 6 billion metric tons per year today. This increase has been essentially monotonic except for seasonal fluctuations as indicated by the observations at Mauna Loa in Hawaii and other observatories. This emission of carbon dioxide has resulted in an increase of approximately 30% in the concentration from 290 parts per million by volume (ppmv) to its present state of approximately 360 ppmv. The result has been the global mean surface temperature curve on this next slide. This is a matter of observational fact and there is no disagreement.

There is little disagreement that the atmospheric radiation balance is affected and mathematical climate model projections indicate that global surface temperatures will according to the International Panel on Climate Change (IPCC) increase significantly by 2100. Most models project in the range from 1.5 to 4.5ºC. The latest IPCC assessment has estimated the range from 1.5 to 6.0ºC. There is general agreement that the global surface temperature and global precipitation will increase. Sea level is increasing largely due to thermal expansion of sea water with a projected central estimate of 0.5 meters. The amount of surface global temperature and sea level increase is uncertain as is indicated in the range of projections. Considerable uncertainty exists in the regional distribution of climate changes and the impacts on agriculture, ecosystems and water resource availability as well as increases in severe weather such as hurricanes.

Adapting to Climate Change

Engineering now enables the adaptation to anticipated climate changes and their consequences. This is different from the traditional use of engineering in coping with existing climate variabilities. The Congress some years ago requested that the United States government prepare an assessment of the impact of climate change on the United States. It is expected that the resulting volume, “Climate Change and America” will be published by the end of the year. The analysis considers the consequences through 2100 for 5 sections of the economy and 16 geographical regions. It uses as a basis for its analysis two climate models from Canada and the U.K. These models yield consistent climate warming projections for the U.S. as a whole, but differ significantly in their regional projections.

Our ability to anticipate future climate changes with its uncertainties presents a dilemma. When do we initiate actions as precautionary measures that will balance the costs of economic and social consequences of climate changes with the costs of engineering and technology to prevent those consequences? When and at what costs do we decide to build dams, seawalls, strengthen bridges? When do we invoke biotechnology to develop droughtand heat-resistant strains of grain? There is a new realization that Earth Systems Engineering can enable adaptation to anticipated climate changes.

Mitigating Climate Change

The nations of the world agreed almost ten years ago in 1992 on a Framework Convention on Climate Change (FCCC) which seeks to "achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The greenhouse gases forcing climate change consist of carbon dioxide, methane, ozone, and nitrous oxide. Because carbon dioxide (CO_2) so dominates the greenhouse gas mixtures except for water vapor, I will focus on CO_2. The overriding issue that occupies governments is the anticipated global climate warming and ways to ameliorate its "dangerous" effects. The treaty leaves the term "dangerous" undefined, but it must include the familiar, if sometimes devastating, phenomena as indicated in the next slide. Ameliorating this warming is arguably one the most difficult and complex challenges facing engineering and technology. The sources of CO_2 are shown in the next slide. Humanity's addiction to fossil fuels (coal, gas and oil) for its energy resources is the root cause; the root solution lies with the decarbonization of the global energy supply. Decarbonization has been proceeding for over a century as seen on the next slide. Global deforestation is a lesser but still a significant contributor.

The issue is complicated because it is of global scope with different regional consequences. It is an issue that cannot be addressed by individual nations. It is an issue that arouses passionate views on all aspects of climate projections and what to do about them. Since initialing of the Climate Convention, governments have been grappling with ways to control atmospheric greenhouse gas concentrations without setting targets for the desired concentrations. Since 1992, five meetings of the Conference of the Parties (COP), the sixth to be convened next month in the Hague, have been held to seek agreement on international action.❖ It is the protocol initialed in Kyoto, Japan in 1997, where agreement was reached to constrain concentrations by limiting the emissions of carbon dioxide and other greenhouse gases and assigning emission targets to the industrialized

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❖ *Since preparation of this paper, the COP6 Conference has ended in disagreement and failure.*

countries, developing countries unwilling to commit to such agreement were given a pass.

The Kyoto agreements require the United States to reduce greenhouse gas emissions to a level 7% below 1990 levels by 2010. Achieving such a reduction would.reduce U.S. fossil energy consumption some 35% below the expected usage in that year. It would involve wrenching changes in the manner of energy production and use in this country. As a supplemental action it was agreed that sequestration of carbon in the biosphere principally in trees could be an ancillary approach. It is to be noted that carbon sequestered by forests and agricultural lands has recently been proposed by the United States to substitute for about 50% of the committed emission reductions. It should also be noted that alternative scenarios focusing more on non CO_2 gases have been proposed by Hansen (PNAS).

There is general agreement that even if successful, the Kyoto protocols will have only minimal effect on the projected climate warming. It is estimated that at most it will reduce global average temperatures by an insignificant amount and according to the IPCC, would require reduction of 60 to 80 percent in emissions to stabilize carbon dioxide concentrations at their present levels. Political controversy continues. China and India and other developing countries remain unwilling to restrict their emissions. The United States Senate, anticipating the wrenching changes that will be required and the fact that all nations are not included in the requirements to reduce emissions, has voted unanimously against actions by our government to implement the Kyoto protocols.

The Engineering and Technology Challenge

Forestalling the projected adverse effects of climate change is Earth Systems Engineering at its most complex. The nations of the world are focused on emission restrictions for industrialized nations with some but uncertain attention to carbon sequestration. As engineers, and in the language of the treaty, we would want to know the target levels of global greenhouse gas concentrations, because it is the concentrations that determine the climate and not the emissions. At the present time, such target levels are undefined.

Setting target levels for concentrations is fraught with uncertainty and controversy. It requires a knowledge of consequences of specific target levels, a knowledge that we presently do not possess. A commonly accepted target roughly doubling pre-industrial levels would yield about 550 ppmv. It is a concentration that it is believed would avoid dangerous interference with the climate system. Doubling present levels would yield about 750 ppmv. If the concentration of 550ppmv is to be achieved through emission reductions, the trajectory of the emission reductions can vary. Economists refer to this as "when flexibility". A trajectory that permits delays in controlling emissions can have the same CO_2 concentration end results as one that does not permit delays.

Engineers and technologists can begin to consider a mind-boggling array of options available for achieving specific levels of greenhouse gas concentrations, whatever target is agreed. Among the available options are those that involve emission reductions from fixed and mobile sources, as well as possibilities for the sequestration of carbon dioxide, and reductions in emissions of other greenhouse gases. In addition there are possibilities for geo-engineering on a global scale. Again, it is not the purpose here to go into detail about energy and sequestration options, but to indicate the wide range of possibilities that an Earth Systems Engineering approach might take.

Emission Reduction:

- Increase the efficiency of both mobile and fixed sources, as for example in the program for the Partnership for a New Generation of Vehicles (PNGV), a joint program of the government and the automobile industry which seeks to increase automobile mileage efficiency.
- Increase efficiency of electric power generation by changing fuels from coal and oil to gas-fired power stations, and by the introduction of turbines and distributed energy sources.
- Increase use of renewable energy sources such as wind power, photovoltaics, biomass and hydropower. They can produce significant amounts of energy, but they are not candidates for base power loads.
- Increase use of already-proven nuclear energy, a CO_2 emission-free energy source. It already occupies a central role in power production, as in France and other countries.
- Continue development of new types of energy systems such as fuel cells for use in automobiles and in fixed locations operating on hydrogen stripped from fossil hydrocarbons.

What is at issue is the evolution of a new global energy system comprised of a variety of energy-generation sources, all of which have the property of restraining the emission of greenhouse gases at a level that will not exceed target concentration levels.

Carbon Sequestration:

Another option is to sequester carbon. Many different ways have been proposed.

- Biospheric sequestration can take the form of growing trees and other plants that use carbon dioxide in the process of photosynthesis. It can be enhanced through biotechnology to produce fast growing trees. Sequestration of carbon in soils is now under consideration.
- Sequester carbon stripped from hydrocarbons by pumping it into deep geological structures with the hydrogen used to power fuel cells.
- Inject CO_2 into oceans at depth to form CO_2 hydrates
- Still other proposals involve fertilizing the oceans by adding iron or phosphorous to increase the production of algae which then would sequester more carbon in the oceans.

Non CO_2 Emission Reductions:

- There are recent proposals to reduce NON CO_2 greenhouse gases such as methane, ozone and nitrous oxide as an effective means of containing greenhouse gas concentrations.

GeoEngineering:

- There are proposals for geo-engineering involving dispersion of dust or injections of SO_2 in the stratosphere to reduce sunlight. These however are totally speculative.

However important evolution of a new low carbon energy system, the sequestration of carbon, and attempts at reducing other greenhouse gases are, if we are to reduce atmospheric concentrations of greenhouse gases, Climate Systems Engineering requires much more. There is the need to anticipate consequences of climate change for ecosystems, water resources, agriculture, health and other activities of humanity. These must not be mere after thoughts, they must become integral parts of requirements. Will new technologies have adverse health effects? Will they result in unwanted effects on ecosystems? Will they be culturally acceptable? The questions are many. Engineers will face the need to collaborate with scientists and engineers from many fields.

Because of the global nature of the issue, there is a political and international engineering dimension. Not only is there a need to engage as we presently do in international consultations and negotiations to arrive at reasonable approaches to achieving agreed concentration levels, but there is also a need to reach out to engineering communities in other countries to enlist their efforts. The task before us is formidable. The course of wisdom may be to take those actions that contribute to emissions reduction and carbon sequestration at low economic cost now and make the investment in research and engineering that can generate the new and advanced technologies that can meet CO_2 concentration targets.

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