CLIMATE CHANGE AND ENERGY OPTIONS: DECISION MAKING IN THE MIDST OF UNCERTAINTY

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Understanding the world's natural systems, and how our own activities may be affecting those systems, are crucial for the long-term well-being of our society and of all the inhabitants of this world. One of the most complex of these is the global climate system. The nature and extent of significant alterations to the global climate system due to increasing emissions of greenhouse gases, resulting from human activity such as energy production and manufacturing processes, is still the subject of considerable uncertainty and, indeed, controversy. However, the possible consequent effects on ecological systems and human society may be of such profound gravity, that continuing research into the causes and effects of climate change, and development of viable technology solutions for mitigation of these effects, are essential. Understanding the global climate system, determining how our activities may be influencing it, and taking responsible actions to protect it for future generations, may be among the greatest challenges that humanity has ever faced.

Background

For over a hundred years, scientists have been carefully gathering and verifying data on the Earth's temperature and precipitation patterns. The most recent data reveal some striking trends:

- 12 of the warmest years in this record occurred during the 17 years prior to 1998. New temperature records continued to be set in 1997, and the average global temperature in 1998 was higher than it had been during the previous 1,000 years [1].
- In large areas of the United States, temperature increases in a range of 2 - 4 °F (1 - 2 °C) have been measured during this century.
- The global average surface temperature has risen approximately 0.7 °C (1.2 °F) in the past 100 years.

Until recently, climate scientists were uncertain whether these developments reflected natural variations in the Earth's climate, or whether in fact human activities contributed to this warming. But in 1995, in the largest peer-reviewed international scientific assessment of any scientific issue ever undertaken, the Intergovernmental Panel on Climate Change – an international body charged with studying this issue – reached the conclusion that the observed increase in global average temperature during the 20th century "is unlikely to be entirely natural in origin" and that "the balance of evidence suggests that there is a discernible human influence on global climate" [2]. Subsequent analyses of these data affirmed that the warming trend in the second half of the 20th century could "exclude purely natural forcing, and [be] attributed largely to the anthropogenic components" [3].

The Earth's climate is the result of extremely complex interactions among the atmosphere, the oceans, the land masses, and living organisms – including human industrial activity – all of which receive energy from the sun. This energy ultimately radiates back into space, but a sufficient fraction is retained in the Earth's atmosphere to maintain an average temperature of approximately 15°C (59°F). This temperature is maintained by energy absorption in heat-trapping gases (the "Greenhouse Gases", or GHG's), which include water vapor, carbon dioxide, ozone, nitrous oxide, methane, and several trace gases of industrial origin (CFC's, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride). Over the course of the Earth's history, living creatures have evolved and adapted to function optimally in this temperature regime, and in turn human society has organized itself to function as well as possible in this climate.

During the past 150 years, atmospheric levels of many GHG's (except water vapor, which is controlled by evapotranspiration and precipitation) have undergone significant increases, recently at an accelerating pace. The connection between GHG emissions and temperature change is not merely that the two seem to be correlated in time, but also that detailed physical models of the atmosphere predict the global warming effect. The magnitude of the effect, however, is subject to considerable uncertainty, as a result of still imperfect knowledge about the interplay between GHG's, atmospheric water vapor, ozone, clouds, aerosols, and particulates. If carbon dioxide concentrations were to double over current levels during the next 100 years – a possible scenario given the trend of economic development – current models predict overall global average temperature increases somewhere between a low estimate of 1 °C (~2 °F) and a high estimate of 3.5 °C (6.5 °F). Furthermore, because of the long residence time of carbon dioxide in the atmosphere, increased CO_2 levels due to fossil fuel combustion will persist long after emissions are reduced [4].

While the low estimate given above may indeed present few challenges, the high estimate – which is just as likely to be true as the low estimate – would have extremely serious consequences. During the last great Ice Age which ended 10,000 to 12,000 years ago, during which the northern U.S. and Europe were covered with a sheet of ice a mile thick, global average surface temperatures were only about 5° C lower than they are today. A global average surface temperature 2 °C higher than current levels would be unprecedented in recent human experience, and an increase of 5° to 6° would correspond to the climate which prevailed during the age of the dinosaurs! It should be noted that these predicted temperature rises are not uniform, but would be significantly higher than the average in specific parts of the Earth, particularly in the Polar regions. Most significantly, these changes are predicted take place, not over geological times of thousands or millions of years, but within a few decades or centuries, far more rapidly than natural ecosystems are able to evolve or adapt.

The possible consequences of this predicted change in global average temperature range from modest, in some cases even benign effects, to severe effects which are difficult to predict with any accuracy but which could be truly catastrophic if they occur. There is a wide variation in the level of confidence with which any specific effect can be forecast [5]; however, all of the following have been predicted on the basis of plausible models and assumptions.

- Increased number and severity of heat waves, droughts, and other extreme weather events which place stress on plant and animal species, including humans.
- Since an increased temperature enables the air to hold larger amounts of water vapor, major changes in precipitation patterns could occur, wreaking havoc with current agricultural practices.
- Ranges and habitats of a wide variety of plant and animal organisms could be affected. This could lead to loss of many species, including many beneficial to humanity, as well as exposure of vulnerable populations to disease-bearing organisms such as mosquitoes, ticks, and rodents.
- Sea levels could rise by 1 foot to as much as 5 feet by year 2100, due to loss of polar and landlocked ice and thermal expansion of the oceans. This would submerge significant areas of low-lying, populated territories, affect the salinity of estuaries and coastal aquifers, and damage or destroy wetlands and coral reefs responsible for much of the ocean's biological productivity. Several scientists have suggested the possibility of even larger sea level rises resulting from breakup of polar ice sheets.
- Projected precipitation increases at higher latitudes could also act to reduce the ocean's salinity and therefore its density. This, in turn, might interfere with oceanic circulation patterns – possibly altering or even suppressing the Gulf Stream which maintains Europe's current temperate climate [6].

Conclusions

In arriving at an appropriate course of action in the face of profound uncertainty about both the magnitude and effects of human-induced climate change, and its impacts on life on Earth and on human economic activity, we must consider both the costs of taking action and the considerable risks of taking no action [7]. International agreements are now under consideration which will begin to limit allowable levels of GHG emissions. Numerous questions still exist among governments, the scientific community, and the general public about the need for such agreements and the most effective technological, economic, and political strategies to achieve such emission limits. A vigorous and well-coordinated research effort is needed to narrow these uncertainties and to develop science and technology options in the case that rapid responses to changing climate conditions become necessary. We recognize, however, that we may never succeed in eliminating all the uncertainties surrounding the climate change issue, and that it may be necessary to take action, sooner rather than later, even in the face of such uncertainties. The longer action is delayed, the more difficult and costly it will be to institute limits on GHG emissions should such limits prove to be necessary.

Many uncertainties remain in the area of Global Change Science, and research still needs to be carried out to reduce these uncertainties. Among these are:

- the effects of clouds, aerosols, particulates, and especially atmospheric water vapor on climate change;
- the coupling between overall global climate change and regional climate variations;
- ocean-atmosphere interactions;
- effects of climate changes on both ecological and social-economic systems.

In addition to continuing to study the basic phenomena of climate change, modern industrial societies must begin to take action to address this issue. Climate change has "massive market transforming potential" [8], with potential impacts on many industry sectors including petroleum and other energy resources, energy production, transportation, agriculture, residential and commercial construction, and not least the chemical industry. Making the transition to a more energy-efficient, less carbon-intensive economy presents a tremendous long-term economic opportunity for those industries willing to undertake the necessary research and development, and invest in the new technologies that will achieve these goals. Some of these opportunities include:

- Chemical manufacturing processes may be redesigned to improve energy efficiency and reduce GHG emissions while reducing or eliminating production of toxic waste. These goals have been summarized in *Technology Vision 2020: The U.S. Chemical Industry* [9] and are the basis of "Green Chemistry" strategies [10].
- Carbon dioxide sequestration may offer a route to partial reduction of net emissions. CO_2 could be captured in industrial processes and removed from the atmosphere by reforestation and planting, which also benefits habitat and biodiversity preservation.
- Alternative energy sources should be developed which minimize GHG emissions, such as advanced fossil-fuel technology, fuel cells, renewable energy technologies such as biomass, wind, and solar energy sources, and nuclear power [11].
- In addition, proposed GHG and carbon emission limits may have a significant *indirect* impact on chemical process industries, since changes in refinery product streams, driven by alternative fuel demand, may affect chemical feedstock availability. A systematic study of such interactions needs to be undertaken, and alternative sources of starting materials identified.

Attaining an understanding of how the global climate system operates and how our own activities may be influencing it, and of undertaking responsible actions to protect that system for the well-being of future generations, may be among the greatest challenges that humanity has ever faced. Arriving at the necessary decisions and taking appropriate actions in the face of substantial uncertainty is neither new nor unfamiliar in our society – corporations always have to make business plans for an uncertain future, and individuals do this whenever they purchase an insurance policy or set up an estate plan. The climate system, on which the global ecology and economy depend, deserves at least the same degree of care and attention. Research on Climate Change and its possible effects must be continued and strengthened, the public must be informed and educated about this issue, industry must adopt proactive strategies for energy conservation and greenhouse gas reductions, and prudent and responsible actions must be undertaken as needed to address this challenge which confronts us all.

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CONCERNS ABOUT CLIMATE CHANGE AND THE ROLE OF FOSSIL FUEL USE

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INTRODUCTION

Climate is defined as the typical behavior of the atmosphere, the aggregation of the weather, and is generally expressed in terms of averages and variances of temperature, precipitation and other physical properties. The greenhouse effect, the ability of certain gases like carbon dioxide and water vapor to effectively trap some of the reemission of solar energy by the planet, is a necessary component to life on Earth; without the greenhouse effect the planet would be too cold to support life. However, human activities are increasing the concentration of carbon dioxide and several other greenhouse gases, resulting in concerns about warming of the Earth by 1-5 K over the next century. Recent increases in global averaged temperature over the last decade already appear to be outside the normal variability of temperature changes for the last thousand years. A number of different analyses strongly suggest that this temperature increase is resulting from the increasing atmospheric concentrations of greenhouse gases, thus lending credence to the concerns about much larger changes in climate being predicted for the coming decades. It is this evidence that led the international scientific community through the Intergovernmental Panel on Climate Change (IPCC, 1996) to conclude (after a discussion of remaining uncertainties) that "Nonetheless, the balance of the evidence suggests a human influence on global climate". More recent findings have further strengthened this conclusion. Computer-based models of the complex processes affecting the carbon cycle have implicated the burning of fossil fuels by an ever-increasing world population as a major factor in the past increase in concentrations of carbon dioxide. These models also suggest that, without major policy or technology changes, future concentrations of CO_2 will continue to increase largely as a result of fossil fuel burning. This paper briefly reviews the state of the science of the concerns about climate change that could result from fossil fuels and other human related emissions.

GASES AND AEROSOLS

Without human intervention, concentrations of many atmospheric gases would be expected to change slowly. Ice core measurements of the gases trapped in ancient ice bubbles indicate this was the case before the last century. However, since the beginning of the industrial age, emissions associated with human activities have risen rapidly. Agriculture, industry, waste disposal, deforestation, and especially fossil fuel use have been producing increasing amounts of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and other important gases. Due to increasing emissions, atmospheric levels of these greenhouse gases have been building at an unprecedented rate, raising concerns regarding the impact of these gases on climate. Some of the gases, such as CFCs, are also responsible for large observed depletions in the natural levels of another gas important to climate, ozone. Of these gases, two, carbon dioxide and methane, are of special concern to climate change and are discussed further.

Carbon Dioxide

Carbon dioxide has the largest changing concentration of the greenhouse gases. It is also the gas of most concern to analyses of potential human effects on climate. Accurate measurements of atmospheric CO_2 concentration began in 1958. The annually averaged concentration of CO_2 in the atmosphere has risen from 316 ppm (parts per million, molar) in 1959 to 364 ppm in 1997. The CO_2 measurements exhibit a seasonal cycle, which is mainly caused by the seasonal uptake and release of atmospheric CO_2 by terrestrial ecosystems. The average annual rate of increase over the whole time period is about 1.2 ppm or 0.4% per year, with the rate of increase over the last decade being about 1.6 ppm/yr. Measurements of CO_2 concentration in air trapped in ice cores indicate that the pre-industrial concentration of CO_2 was approximately 280 ppm. This data indicates that carbon dioxide concentrations fluctuated by ± 10 ppm around 280 ppm for over a thousand years until the recent increase to the current 360+ ppm, an increase of over 30%.

Why has the atmospheric concentration of CO_2 increased so dramatically? Analyses with models of the atmosphere-ocean-biosphere system of the carbon cycle, in coordination with observational analyses of the isotopes of carbon in CO_2, indicate that human activities are primarily responsible for the increase in CO_2. Two types of human activities are primarily responsible for emissions of CO_2: fossil fuel use, which released about 6.0 GtC into the atmosphere in 1990, and land use, including deforestation and biomass burning, which may have contributed about 1.6 ± 1.0 GtC in addition to that from fossil fuels. Evaluations of carbon releases from vegetation and soils based on changes in land use indicate that land use decreased carbon storage in vegetation and soil by about 170 Gt since 1800. The added atmospheric carbon resulting from human activities, as described above, is redistributed within the atmospheric, oceanic, and biospheric parts of the global carbon cycle, with the dynamics of this redistribution determining the corresponding rise in atmospheric CO_2 concentration. In the future, as the amount of CO_2 increases in the atmosphere and in the ocean, it is expected that the oceans will take up a smaller percentage of the new emissions. Analyses of the carbon budget have implied that there is a mismatch between observed levels of CO_2 and known loss processes. This discrepancy suggests that a missing carbon sink has existed during recent decades. This sink now appears to be largely explained through increased net carbon storage by the terrestrial biomass stimulated by the CO_2 fertilization effect (increased growth in a higher CO_2 concentration atmosphere).

Carbon dioxide is emitted when carbon-containing fossil fuels are oxidized by combustion. Carbon dioxide emissions depend on energy and carbon content, which ranges from 13.6 to 14.0 MtC/EJ for natural gas, 19.0 to 20.3 for oil, and 23.9 to 24.5 for coal. Other energy sources such as hydro, nuclear, wind, and solar have no direct carbon emissions. Biomass energy, however, is a special case. When biomass is used as a fuel, it releases carbon with a carbon-to-energy ratio similar to that of coal. However, the biomass has already absorbed an equal amount of carbon from the atmosphere prior to its emission, so that net emissions of carbon from biomass fuels are zero over its life cycle.

Human-related emissions from fossil fuel use have been estimated as far back as 1751. Before 1863, emissions did not exceed 0.1 GtC/yr. However, by 1995 they had reached 6.5 GtC/yr, giving an average emission growth rate slightly greater than 3 percent per year over the last two and a half centuries. Recent growth rates have been significantly lower, at 1.8 percent per year between 1970 and 1995. Emissions were initially dominated by coal. Since 1985, liquids have been the main source of emissions despite their lower carbon intensity. The regional pattern of emissions has also changed. Once dominated by Europe and North America, developing nations are providing an increasing share of emissions. In 1995, non-Annex I (developing countries; includes China and India) nations accounted for 48 percent of global emissions.

Future CO_2 levels in the atmosphere depend not only on the assumed emission scenarios, but also on the transfer processes between the major carbon reservoirs, such as the oceans (with marine biota and sediments) and the terrestrial ecosystems (with land use changes, soil and forest destruction. Recent work for the new IPCC assessment show, based on projections of fossil-fuel use and land use changes, that the concentration of CO_2 are expected to increase well above current levels by 2100 (75 to 220 % over pre-industrial concentrations). None of these scenarios leads to stabilization of the CO_2 concentration before 2100.

Methane

Although its atmospheric abundance is less than 0.5 percent that of CO_2, on a molecule by molecule basis, a molecule of CH_4 is approximately 50 times more effective as a greenhouse gas in the current atmosphere than CO_2. When this is combined with the large increase in its atmospheric concentration, methane becomes the second most important greenhouse gas of concern to climate change. Based on analyses of ice cores, the concentration of methane has more than doubled since preindustrial times. The current globally averaged atmospheric concentration of methane is about 1.75 ppm.

Continuous monitoring of methane trends in ambient air from 1979 to 1989 indicates that concentrations had been increasing at an average of about 16 ppb (~1percent per year). During much of the 1990s, the rate of increase in methane appeared to be declining. Although the cause of the longer-term global decline in methane growth is still not well understood, it may be that much of the earlier rapid increase in methane emissions from agricultural sources are now slowing down. However, since 1997 the CH_4 growth rate has increased to about 10 ppb per year. There are some indications that this increase in the growth rate may be due to a response of emissions from wetlands in the Northern Hemisphere responding to global warming over the last decade.

Methane emissions come from a number of different sources, both natural and anthropogenic. One type of human related emissions arise from biogenic sources from agriculture and waste disposal, including enteric fermentation, animal and human wastes, rice paddies, biomass burning, and landfills. Emissions also result from fossil fuel-related methane sources such as natural gas loss, coal mining, and the petroleum industry. Methane is emitted naturally by wetlands, termites, other wild ruminants, oceans, and hydrates. Based on recent estimates, current human-related biogenic and fossil fuel-related sources for methane are approximately 275 and 100 $TgCH_4$/yr while total natural sources are around 160 $TgCH_4$/yr.

Sulfuric and other aerosols

Emissions of sulfur dioxide and other gases can result in the formation of aerosols that can affect climate. Aerosols affect climate directly by absorption and scattering of solar radiation and indirectly by acting as cloud condensation nuclei (CCN). A variety of analyses indicate that human-related emissions of sulfur, and the resulting increased sulfuric acid concentrations in the troposphere, may be cooling the Northern Hemisphere sufficiently to compensate for much of the warming expected from greenhouse gases. Volcanic emissions can influence climate for short periods (1 to 3 years) through emissions of sulfur dioxide into the lower stratosphere.

Over half of the sulfur dioxide, SO_2, emitted into the atmosphere comes from human-related sources, mainly from the combustion of coal and other fossil fuels. Most of these emissions occur in the Northern Hemisphere. Analyses indicate that anthropogenic emissions have grown dramatically during this century. Other SO_2 sources come from biomass burning, from volcanic eruptions, and from the oxidation of di-methyl sulfide (DMS) and hydrogen sulfide (H_2S) in the atmosphere. DMS and H_2S are primarily produced in the oceans. Atmospheric SO_2 has a lifetime of less than a week, leading to formation of sulfuric acid and eventually to sulfate aerosol particles. Gas-to-particle conversion can also occur in cloud droplets; when precipitation doesn't soon occur, the evaporation of such droplets can then leave sulfate aerosols in the atmosphere.

RADIATIVE FORCING

A perturbation to the atmospheric concentration of an important greenhouse gas, or the distribution of aerosols, induces a radiative forcing that can affect climate. Radiative forcing of the surface-troposphere system is defined as the change in net radiative flux at the tropopause due to a change in either solar or infrared radiation. A positive radiative forcing tends on average to warm the Earth's surface; a negative radiative forcing tends to cool the surface. Analyses of the direct radiative forcing due to the changes in greenhouse gas concentrations since the late 1700s give an increase of about 2.3 Wm^{-2}. To put this into perspective, a doubling of CO_2 from pre-industrial levels would correspond to about 4 Wm^{-2}; climate models studies indicate this would give 1.5 to 4.5 C increase in global temperature. Approximately 0.5 Wm^{-2} of the increase has occurred within the last decade. By far the largest effect on radiative forcing has been the increasing concentration of carbon dioxide, accounting for about 64 percent of the total change in forcing.

Changes in amounts of sulfate, nitrate, and carbonaceous aerosols induced by natural and human activities have all contributed to changes in radiative forcing over the last century. The direct effect on climate from sulfate aerosols occurs primarily through the scattering of solar radiation. This scattering produces a negative radiative forcing, and has resulted in a cooling tendency on the Earth's surface that counteracts some of the warming effect from the greenhouse gases.

Changes in tropospheric and stratospheric ozone also affect climate, but the radiative effects from the increase in tropospheric ozone over the last century and the decrease in stratospheric ozone over recent decades have had a relatively small combined effect compared to CO_2. Changes in the solar energy output reaching the Earth is also an important external forcing on the climate system. The Sun's output of energy is known to vary by small amounts over the 11-year cycle associated with sunspots and there are indications that the solar output may vary by larger amounts over longer time periods. Slow variations in the Earth's orbit, over time scales of multiple decades to thousands of years, have varied the solar radiation reaching the Earth, and have affected the past climate. Solar variations over the last century are thought to have had a small but important effect on the climate, but are not important in explaining the large increase in temperatures over the last few decades.

Evaluation of the radiative forcing from all of the different sources since pre-industrial times indicates that globally-averaged radiative forcing on climate has increased. Because of the hemispheric and other inhomogeneous variations in concentrations of aerosols, the overall change in radiative forcing is much greater or much smaller at specific locations over the globe.

THE TEMPERATURE RECORD AND OTHER CLIMATE INDICATORS

There is an extensive amount of evidence indicating that the Earth's climate has warmed during the past century. Foremost among this evidence are compilations of the variation in global mean sea surface temperature and in surface air temperature over land and sea. Supplementing these indicators of surface temperature change is a global network of balloon-based of atmospheric temperature since 1958. As well, there are several indirect or *proxy* indications of temperature change, including satellite observations (since 1979) of microwave emissions from the atmosphere, and records of the width and density of tree rings. The combination of surface-, balloon-, and satellite-based indicators provides a more complete picture than could be obtained from any given indicator alone, while proxy records from tree rings and other indicators allow the temperature record at selected locations to be extended back for a thousand years. Apart from temperature, changes in the extent of alpine glaciers, sea ice, seasonal snow cover, and the length of the growing season have been documented that are consistent with the evidence that the climate is warming. Less certain, but also consistent, changes appear to have occurred in precipitation, cloudiness, and interannual temperature and rainfall variability.

Thermometer-based measurements of air temperature have been systematically recorded at a number of sites in Europe and North America as far back as 1760. However, the set of observing sites did not attain sufficient geographic coverage to permit a rough computation of the global average land temperature until the mid- nineteenth century. Land-based, marine air, and sea surface temperature datasets all require rather involved corrections to account for changing conditions and measurement techniques. Analyses of these records indicates a global mean warming from 1851 to 1995 of about 0.65±0.05°C.

In addition to limited sampling of temperature with altitude, satellite-based sensors, known as microwave sounding units (MSUs), are being used to examine global temperature changes in the middle troposphere (mainly the 850-300 HPa layer), and in the lower stratosphere(~ 50-100 Hpa). None of the channels sample at the ground. The MSU measurements have been controversial because some earlier versions of the satellite dataset have indicated a cooling in the lower troposphere in contrast to the warming from the ground-based instruments. However, several errors and problems (e.g., due to decay in the orbit of the satellite) with the MSU data have been found, and the latest analyses of MSU corrected for these problems show a warming, albeit somewhat smaller than that found at the ground.

Proxy temperature indicators, such as tree ring width and density, the chemical composition and annual growth rate in corals, and characteristics of annual layers in ice cores, are being used at a number of locations to extend temperature records back as much as a thousand years. The reconstruction indicates the decade of the 1990s has been warmer than at any time during this millennium and that 1998 was the warmest year in the 1000-year record.

Recent studies with state-of-the-art numerical models of the climate system have been able to match the observed temperature record well but only if they include the effects of greenhouse gases and aerosols. These studies indicate that natural variability of the climate system is not sufficient to explain the increasing temperatures in the 1990s.

CONCLUSIONS

Human activities already appear to be having an impact on climate. The latest evaluation for future global warming by 2100, relative to 1990, for a business-as-usual set of scenarios based on varying assumptions about population and economic growth is 1.3 to almost 5 K. Potential economic, social and environmental impacts on ecosystems, food production, water resources, and human health could be quite important, but require much more study. A certain degree of future climatic change is inevitable due to human activities no matter what policy actions are taken. Some adaptation to a changing climate will be necessary. However, the extent of impacts and the amount of adaptation will depend on our willingness to take appropriate policy actions. The consensus grows that we must follow a two-pronged strategy to conduct research to narrow down uncertainties in our knowledge, and, at the same time, take precautionary measures to reduce emissions of greenhouse gases.

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THE BRIDGE FROM COLD FACTS AND HOT RHETORIC TO RATIONAL CLIMATE POLICY

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ABSTRACT: The academic community must expand its role in the political debate over Climate Change policy. The field is characterized by a cacophony of competing scientific claims, scare tactics, and propaganda. Scientists, particularly those in the academy, are badly needed in the role of upholders of the principles of scientific inquiry and standards of evidence upon which rational public policy depends. They should weigh into the conflict more heavily, not on one side or the other, but to point out when the participants on either side are exceeding the bounds of rational analysis. This will not only contribute to more informed policy but also preserve the integrity of science which is essential for continued human progress.

PAPER:

The theme of my presentation concerns the importance of academic and intellectual institutions, a category which clearly includes the American Chemical Society, to the scientific and policy debate over Climate Change and the Kyoto Protocol.

These institutions are much more than simply private associations of their members. They are also major *public* institutions, dedicated to public service as well as to research and education. This role requires the institutions, or, more precisely, their members to go beyond the ivory tower of intellectual inquiry by bringing scientific rigor to bear on important national policy debates so that we choose polices that are scientifically defensible and economically realistic.

This is an important function. It is also an exceedingly difficult one. I have a deep respect for science, and for those who devote their lives to it. I learned through a 12-year affiliation with the University of Rochester the power and value of the scientific method -- the clear statement of testable hypotheses, careful testing and evaluation of evidence, gloves-off peer review, and replication. The scientific approach and the pursuit of knowledge have been and will continue to be two of the great engines of human progress. A commitment to seek the truth no matter where the quest leads reflects a calling of the highest order. In the words of Norbert Wiener, the founder of cybernetics, a good scientist "has a consecration which comes entirely from within himself."[1]

These values make the objective of combining science with relevance to the current Climate Change debate not only lofty but also daunting. The scientific values of careful statement, reliance on evidence, relentless pursuit of truth, and willingness to confess error sadly are not the currency of the political marketplace. Indeed, too often the values that hold sway in politics are the exact reverse of those that govern the scientific enterprise. Science in public policy is used increasingly as a campaigning enterprise instead of a means of measuring evidence and seeking truth. As a nobel laureate recently observed, in science facts matter and perceptions are negotiable while in politics perceptions matter and facts are negotiable.

In 1961, the distinguished historian Daniel J. Boorstin published a prescient book called *The Image: A Guide to Pseudo-Events in America.*[2] Its thesis is that many aspects of American life, including politics, are losing their connection to reality. Instead, they are dominated by "pseudo-events," events staged to attract the attention of the megaphone of the media, and which manipulate opinion by exploiting the gap between what we need to know and what we can know.

If Boorstin was worried in 1961, when his book appeared, he must be horrified by today's world. The triumph of Gresham's Law seems complete as the false coin of image drives out the gold of truth. The spinners often seem actively hostile to thinking about reality, as if any need to consider truth would only inhibit their creativity in crafting an image to promote what they judge to be worthy goals. We are living in a time in which the belief that the end justifies the means is all too frequently dominant.

One of the most disturbing aspects of the debate over Climate Change is the extent to which it has been driven by pseudo-events and pseudo-arguments. These are displacing good science and reliance on evidence with synthetic truths and treating as settled matters that are extremely uncertain.

This may sound like rhetoric, so let me provide some examples.

First, I will begin with a few things that are known about Climate Change. The Greenhouse Effect is indeed a fact. Certain gases, such as CO_2 and -- far more important -- water vapor do trap some of the sun's warmth. This is a good thing, since without it the temperature of the earth would be about zero degrees Fahrenheit.

Second: The temperature of the earth has gone up over the past 150 years by about one degree Fahrenheit. At least, it appears to be about a degree. Measurements from the 19th Century are inexact, so it is hard to be sure, but we are certain it has increased.

Fact three: During the past 150 years the atmospheric concentration of CO_2 has risen from about 278 parts per million to 365 ppm. It is commonly stated as a certainty, but the methodology underlying the estimates of CO_2 concentrations in the 19th Century has been criticized as possibly underestimating these pre-industrial levels, and thus overstating the increase.[3] It is clear that we are only beginning to understand the complexities of the global carbon cycle.

Now, those three facts exhaust most of what is known with reasonable certainty about the risk of human-induced Climate Change. Everything else is immersed in a sea of uncertainty and subject to debate. For example, it is often stated that human activity has caused the increase in CO_2 concentration because burning fuel releases CO_2. This is a reasonable hypothesis — and I stress *hypothesis*. But other hypotheses are also reasonable. There is strong evidence that at times in the history of the earth, CO_2 concentrations were as much as 20 times as high as they are today, and this was long before the age of fossil fuels.[4]

Take another "known fact" that is simply another hypothesis: It is asserted that since CO_2 concentrations have gone up over the past century, and so has the temperature, then the CO_2 caused the temperature rise. This sounds logical, but it does not fit the data or climate history. Most of the rise in temperatures occurred before 1940, and thus preceded most of the increase in CO_2 concentration. Despite the increase in CO_2, over the past 20 years, highly accurate satellite data show no increase in lower atmosphere temperature. And, satellite data closely correlate with weather balloon measurements.

So, to what do we attribute the rise in temperature over the past century? One hypothesis that fits the data is that increases in temperature are correlated with solar activity -- sun spots.[5] And it is entirely possible that the chain of causation is the reverse of conventional wisdom — rises in temperature might cause increases in CO_2 concentrations as the oceans re-balance. Finally, the end of the last century marked the end of a "little ice age," so natural variability is a major factor in explaining this century's temperature increase.

If you start with the assumption that CO_2 is primarily responsible for the rise in temperature over the past century, then it is also logical to assume that further increases in the release of greenhouse gases will cause further rises in temperature. This is a legitimate concern but it still is only a hypothesis. The models that predict warming as a result of increases in greenhouse gases (GHGs) rely heavily on assumptions about a water vapor feedback cycle, assumptions that have little empirical basis. If this feedback cycle does not exist or was modest then increases in GHG concentrations would have very little impact on temperature.

The list of other "facts" that turn out to be less than solid grow with the intensity of the rhetoric. Mark Twain once observed that he wasn't troubled by all the things that people don't know. He was troubled by all the things they do know that just aren't so. This applies to Climate Change. Predictions of the rise in temperature to be expected as a result of human activity has been steadily reduced. In 1990, the Intergovernmental Panel on Climate Change (IPCC) best estimate was an increase of 3.2° C. by the year 2100. Five years later, the estimate was down to a 2.0° C. But this does not reflect the latest research. Some observers believe that advances in knowledge and models should reduce the best estimate to 1 ° C .

In spite of reduced estimates of temperature increase, dubious predictions abound. One reads that global warming will cause catastrophic rises in sea levels, or about an increase in infectious diseases, or rising deaths due to heat waves, or a steady stream of record high temperatures, or more hurricanes and other extreme weather events. None of these bugaboos are probable. Few are even remotely plausible. None are supported by science. All represent the politics of doom to advance through fear an agenda that cannot stand on its own merits.

Since in our Alice in Wonderland paradigm, policy is based on "sentence first, trial afterwards," it is important that scientists become more involved in this debate. And it is crucial that they maintain focus on applying the rigors of science, because they have a powerful role to play in helping to re-focus the debate back on rationality, evidence, and fact. Scientists can take a lead in applying relentless skepticism to the claims of all parties, because of a primary allegiance to truth, to reality. Most of the parties to the debate have interests that expose them to temptation to subordinate objective reality to their particular interests. Knowing that their claims will receive close scrutiny from disinterested scientists is the best way to build resistance to this temptation.

I am not exempting industry from this prescription, either. I represent the petroleum industry, a special interest which has a large economic stake in the outcome of this debate. No one should accept automatically anything said by me or any other industry representative. Whatever the topic, the audience should bring scientific skepticism to bear and ask: "Tell me why you think that -- show me the evidence, and show me your logic."

However, since I am from industry I am used to such skeptical challenging. While I may not always enjoy it, it is good for me, and for others who engage in advocacy. I do not ask that scientists go easy on me. But, in fairness, their vigilance should be extended to others, since it would be equally foolish to accept without question the views of other participants. Advocates of the Kyoto Protocol wrap themselves in robes of concern for the environment. Some of this is real, but some of it is gamesmanship. They are also special interests of various sorts, including economic ones. Some businesses see the possibility of subsidies, market share, and competitive advantage. Other parties see chances for government grants, foreign travel, and lucrative future consulting. Some government officials see opportunities for power, office, and bureaucratic aggrandizement. Environmental organizations see a lever to promote a broader agenda, one that often crosses the border from concern about the environment into opposition to industrial activity and to the personal freedom and mobility that are among our core values as Americans.

So I urge all scientists to treat everyone's claims with even-handed skepticism.

This role of imposing scientific order and honesty on the public debate is only part of the scientists' job, though. It is surprising how little we know for certain about the Climate Change issue. A serious criticism of the Clinton Administration is for its rush to judgment and hyping of a supposed solution before we even know if a serious problem exists. This has diverted energy from thoughtful efforts to explore the existence and scope of the threat and to develop actions that are consistent with our state of knowledge.

For example, we need to know more about past CO_2 levels. The history of the pre-satellite temperature record needs close scrutiny, and serious concerns about possible distortions need to be resolved. While I have dismissed concerns about extreme weather events, infectious diseases and similar issues, there is no doubt that these are matters of concern to the public. They need continuing scientific attention. Research is needed on solar activity and the mechanism by which solar activity impacts global temperature.

This only begins the list of scientific tasks on Climate Change. We need better climate models to reduce the variability between models and the enormous uncertainty surrounding projected impacts. This means we need more scientific knowledge about the impact of clouds, water vapor feedback cycles, snow and ice accumulation and reflectivity, the phenomenon of desertification, and other scientific dimensions of climate issues.

Often, when I raise these issues I am accused of using scientific uncertainty as an excuse for inactivity and delay. This mis-states the issue and my position. Our choices are not between action or inaction but between responsible and irresponsible actions. Thus my final point concerns the Climate Change issue as a problem in public policy, as a problem in choosing actions that are consistent with our state of knowledge and economic objectives.

My own background is not in science but in economics, business, and policy analysis. To those of my ilk, the details of the Climate Change issue are complicated, but the basic structure of the problem is simple -- Climate Change is a problem in decision-making under conditions of uncertainty. Those of us in business confront similar problems every day, and we know the rules for dealing with them.

The first rule is to be slow to commit. Until you must, do not bet your company (or your country) on something that might turn out to be an error. If at all possible, postpone major decisions while you reduce uncertainties.

Given this rule, the first question to ask is, "Do we have time?" With respect to Climate Change, the answer is clearly, "Yes." We do not need to drastically reduce emissions in the short term because nothing we do in the next 15 or 20 years will have any appreciable impact on the world's average temperature in 2050 or 2100. In fact, nothing the U.S. does in the next 10 or 20 years will have much impact on the atmospheric concentration level of greenhouse gases in the year 2020. According to the former Chairman of the Intergovernmental Panel on Climate Change, the effect of the Kyoto Protocol on CO_2 concentration levels in 2010 is four-tenths of one percent (0.4%). And it would not be much greater in the following decade.

Since concern should be with the total accumulation of CO_2 and not with emissions *per se*, decisions on accelerated reductions in emissions can be safely postponed. This fact is crucial, because the costs of these reductions are exceedingly sensitive to timing. Many capital investments, including those in energy, are long term. If change can be deferred until current equipment reaches the end of its useful life, and can be replaced by more efficient technology, costs will decline drastically.

Recently, some confusion over the potential costs of Kyoto was triggered by the Administration's release of an optimistic study by the Council of Economic Advisors (CEA). The Council reached its rosy conclusion only by three assumptions, all of them unrealistic. It assumed the U.S. could meet 80 per cent of its emission reduction obligations by buying credits from abroad. Put another way, only 20 percent of our obligations would be met by domestic action. The Kyoto Protocol does not provide for this and no mechanism for accomplishing such a result is in place. CEA made two other critical assumptions: First, that there is a truly global emissions trading system in place, even though 138 developing countries are exempted from the Protocol. Second, that electric utilities would largely switch from coal to natural gas in 10 years. This is economically impractical. Dr. Boorstin might call the Council's work a pseudo-analysis.

A more realistic recent appraisal came from the Energy Information Administration, which estimated that Kyoto could, by 2010, raise gasoline prices 53 percent, raise electricity rates 86 percent, and reduce GNP by 4.2 percent.[6]

Make no mistake. A commitment to link decisions on Climate Change to the true state of knowledge and advances in it will produce long term environmental and economic benefits.

This leads logically to the second rule for making decisions under uncertainty: Invest in information. Spend money to narrow the range of possibilities. Use sensitivity analysis — what information forms the hinge of the decision, and how can we get it? We need to invest in gaps in climate science that have been identified by the National Research Council. We need better climate models. We also need to invest in analyzing basic issues. And we need to invest in creating contingency plans.

The third rule is called "no regrets." Look for actions that will produce benefits under any set of circumstances. Business has developed a list of emission-control and policy actions that will be worthwhile even if the threat of Climate Change turns out to be a hobgoblin, and we have shared it broadly. In contrast, the Administration policy of committing to near-term emissions rollbacks, regardless of the state of knowledge or the timing of investment decisions, is guaranteed to cause a lot of regret.

The final rule is to consider alternatives. It is a truism that the further ahead you try to predict, the greater the number of uncertain factors, and the larger the probability that any single guess will be wrong. This wisdom that a broad net should be cast to be sure that all alternatives are considered certainly applies to Climate Change. Even if the problem turns out to be real, it is likely that a crash program of prevention is the wrong option. In much of the world the impact of warming could be neutral or even benign. In other cases, it might make more sense to commit resources to adaptation. These options need serious consideration and analysis, and serious scientific work. They are not getting it to the extent that they should.

These four rules — use time as a friend rather than an enemy; invest in information; look for "no regrets" actions; consider all the alternatives — provide the basis for a sound national and international policy on Climate Change. Their wisdom is thoroughly supported by the facts and by the logic of a learn, act, learn strategy.

So, to return to my initial theme — the role of scientists — I urge all scientists to hold firm to their scientific habits of mind in their work on the Kyoto Protocol, whether that work takes the form of research, education, or participation in the policy debate. I think the Administration is acting in the unfortunate tradition of political leaders who try, by command or demagoguery, to repeal the laws of reality when these conflict with their ideology.

Science and the scientific method should not be campaigning tools, used to gain advantage by promoting fear and stifling debate. As Ted Koppel eloquently observed, in a discussion he had with Al Gore on *Nightline* several years ago: "The measure of good science is neither the politics of the scientists nor the people with whom the scientist associates. It is the immersion of hypothesis into the acid of truth. That's the hard way to do it, but it's the only way that works."

It is heartening that a TV newsperson can be quoted on the importance of science and truth. These values need to be restored as part of the shared consciousness of the society. Actions do have consequences and a frightened society can talk itself into stagnation. Looking at the future, the greatest threats to continued progress are the illusion of knowledge and the corrosive effects of anxiety run amok. It is the job of scientists to replace the illusion with real knowledge, and the anxiety with reason. Beyond producing a more informed climate policy, a renewed commitment to science and engineering provides society with the foundation for human creativity and progress.

NOTES

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1. Norbert Wiener, quoted in *Bartletts*, p. 691.

2. Harper Colophon Books, 1964 (paperback edition).

3. Tom V. Segalstad, "Carbon cycle modeling and the residence time of natural and anthropogenic atmospheric CO_2: on the construction of the 'Greenhouse Effect Global Warming' dogma," in Roger Bate (ed.), *Global Warming: The Continuing Debate*, European Science and Environment Forum, Cambridge, England, Jan. 1998, pp. 184, 187-89.

4. Arthur B. Robinson, Sallie L. Baliunas, Willie Soon & Zachary W. Robinson, "Environmental Effects of Increased Atmospheric Carbon Dioxide," Jan. 1998 (Published by the Oregon Petition Project).

5. Virginia Postrel & Steven Postrel, "Stars in Her Eyes: An Interview with Sallie Baliunas," *Reason*, Oct. 1998, p. 42.

6. EIA, *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity* (Oct. 9, 1998).

unit of combustion products. Two thirds of coal combustion products are CO_2 versus one third of methane.

$$2Coal(CH) + 2\tfrac{1}{2}O_2 \rightarrow 2CO_2 + H_2O$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Therefore, the utilization of the methane contained in natural gas hydrate would not only ensure the adequacy of world energy resources, but would also mitigate global climate change.

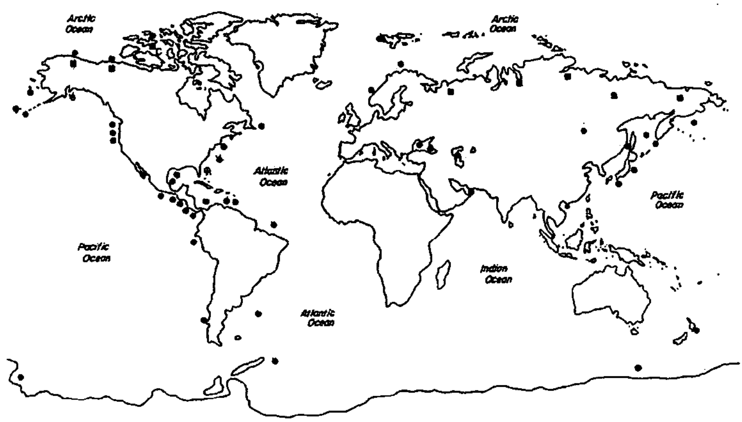

Figure 2. Map of In-Situ Hydrate Locations
Reference: Kvenvolden, K. A., *Chem. Geol.*, 71, 431 (1988).

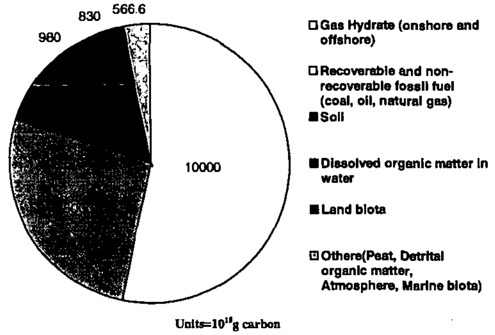

Figure 3. Distribution of organic carbon in earth (excluding dispersed organic carbon such as kerogen and bitumen)
Reference: Keith A. Kvenvolden, *International Conference on Natural Gas Hydrates*, Ann. N. Y. Acad. Sci. vol. 715, 232-246 (1994)

PHASE EQUIRIBRIA

For studying about methane gas recovery from hydrates, phase equilibria between the hydrate phase and the gas phase is very important. The fundamental model is based on statistical thermodynamics and developed by van der Waals and Platteeuw (1959). Later, Parish and Prausnitz (1972) modified it and recently, a distortion model was developed by Lee and Holder (1999). Figure 4 shows the three phases curves for several hydrates. Q_1 is the triple point and Q_2 is the quadruple point. As can be seen, low temperature and high-pressure favor hydrate formation.

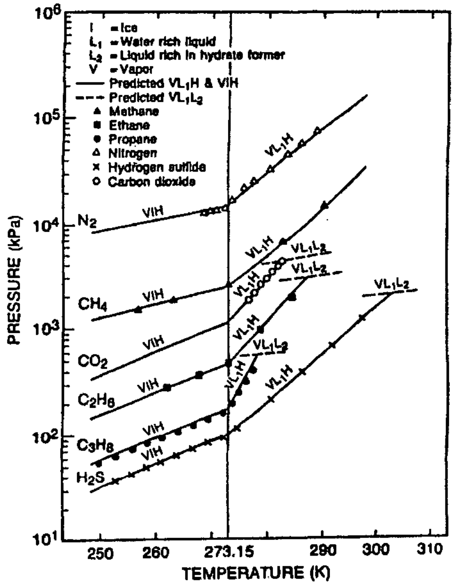

Figure 4. Hydrate Forming Conditions for Several Gases.
Reference: Holder et al., *Review in Chemical Engineering*, Vol. 5,1-70 (1988).

THE RECOVERY OF GAS FROM HYDRATED RESERVOIRS

First, solid hydrates probably need to be dissociated for gas recovery from hydrates. The dissociated gas can then be transported in the same manner as conventional natural gas. Dissociation of gas hydrates can be accomplished in three ways. The first method is thermal injection, the second is pressure reduction and the last is slurry mining.

When heat is added at constant pressure, the system temperature can rise up to the dissociation temperature. At the dissociation temperature, all heat that is added is spent on hydrate dissociation. The energy required to dissociate hydrate ranges from 50 kJ/mole (for methane) to 130 kJ/mole (for propane) (Holder, 1988). The problem with this method is the heat lost to reservoir rock and water. Without heat loss the injected energy is about 10% of the recovered energy. With heat loss the injected energy may exceed the heating value of the gas. This method is also expensive and has to simultaneously move hot fluid downward and gas upward (Max et al, 1997).

The second technique is the depressurization technique. It operates by lowering the pressure in an adjacent gas reservoir. When the pressure reaches the dissociation pressure, gas hydrates at the interface convert to gas and water. This technique has been used in the Messoyhaka gas field in the western Siberia hydrocarbon province (Max et al., 1997). The last method, slurry mining, has not studied yet but is suggestive of grinding up the ocean bottom to recover a slurry of solid hydrates which are likely to dissociate in the riser. Holder et al. (1984) notes that depressurization and hot water injection seem to be the most promising techniques for further evaluation because of lower heat loses compare to steam injection.

A complication of producing gas from hydrate is the possible formation of gas hydrates in the transportation lines. There are four thermodynamic ways to prevent hydrate formation (Sloan, 1997). They are 1) remove the water (it can lower the dew point), 2) keep the system temperature higher than hydrate formation temperature, 3) keep the system pressure lower that hydrate formation pressure, and 4) use inhibitors. These methods are used individually or jointly in production operations today.

Recently, research about replacement of naturally occurring methane hydrates with carbon dioxide hydrate has been also studied. Methane gas hydrates need higher pressure to be stabilized compare to carbon dioxide gas hydrates. Over a certain pressure, methane gas hydrate is unstable, while carbon dioxide gas hydrate is stable. However, very complex phase behaviors are likely to make this process difficult.

CONCLUSION

Natural gas, primarily methane is an excellent fuel for combustion for a number of reasons. Methane produces less carbon dioxide per mole than any other fossil fuel when it is used as fuel. Thus, it can reduce the amount of anthropogenic emissions of dioxide gas, which may cause a green house effect. In addition, natural gas contains very little sulfur or phosphates that can cause air pollution. Additionally, the amount of fossil fuel in hydrate form is twice as large as in all other forms. Thus, methane gas hydrate has a potential to be used as a new energy source.

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Methane Hydrates: Fuel of the Future?

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ABSTRACT

Gas hydrates are crystalline solids that form from mixtures of water and light natural gas such as methane, carbon dioxide, ethane, propane and butane. They are of considerable interest for their potential as an energy resource and for their role in global warming. From an energy resource point of view, the enormous amounts of methane hydrate under the ocean and beneath arctic permafrost represent an estimate 53% of all fossil fuel (coal, oil, natural gas) reserves on earth, about 10,000 gigatons. The difficulty with recovering this source of energy is that the fuel is in solid form and is not amenable to conventional gas and oil recovery techniques.

INTRODUCTION

Gas hydrates are crystalline molecular complexes formed by the physical combination of water and low molecular weight gases. They have the general formula $M_n(H_2O)_p$, where one or more hydrate forming molecules M called "guest" associated with p "host" water molecules. The guest gas molecules are physically encaged in interstices or cavities in the lattice structure formed by the water molecules that are held by hydrogen bonds (Holder et al, 1988). There are three different kinds of gas hydrates according to its structure; Structure I, structure II and structure H. A typical illustration of structure I gas hydrate is shown in figure 1 (Sloan, 1997).

Estimations of world hydrate reserves are very high but somewhat uncertain. Kvenvolden estimated it as 10^{16} m^3 (1994). Figure 2 gives sites with evidence of either on-shore or off shore hydrate deposits and figure 3 gives the relative magnitude of gas hydrates as a reservoir of organic carbon on earth. Methane hydrates, which form structure I gas hydrate, store immense amount of methane and occur in abundance in marine and Arctic sediments (Kvenvolden, 1994). One unit volume of methane hydrates can contain over 160 volumes of gas and less than one unit of water at standard conditions. According to estimations by Collett, as much as 200,000 trillion cubic feet of methane may exist in hydrates in the U.S. permafrost regions and surrounding waters (DOE, 1998). Because of its huge quantities, methane hydrates represent a potentially enormous natural gas resource.

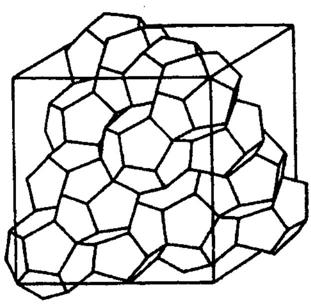

Figure 1. Unit cell of a gas hydrate of structure II
Reference: Mak, T.C.W., McMullan, R. K., *J. chem. Phys.*, 42, 2732 (1965).

Another important factor is that methane is less carbon-intensive fuel than coal or oil. Methane from hydrates (or other sources) produces only half as much carbon dioxide as coal per

THE FUTURE OF NUCLEAR ENERGY

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KEYWORDS: Nuclear, Electricity, Waste

A PERSPECTIVE ON NUCLEAR POWER DEVELOPMENT

Nuclear power started with the discoveries before and during World War II, a remarkable time in our history. The defining event took place at the University of Chicago on December 2, 1942 when it was demonstrated that nuclear fission could be sustained and controlled. This ushered in the nuclear age.

Following World War II, the United States government and the University of Chicago organized Argonne National Laboratory (ANL) to continue research into peaceful uses of this awesome power. Soon there was need for a site that could host the construction of experimental nuclear power plants. Idaho was chosen by then Argonne director Walter Zinn. It led to the construction of the Experimental Breeder Reactor I (EBR-I), the first reactor to produce electricity, and the boiling water reactor (BORAX), which tied into the grid and made Arco, Idaho the first town in the world to be lit with nuclear energy. From this simple beginning – a string of eight dim light bulbs and four hours of power to a small desert town – nuclear power has grown to account for about 17% of energy production world wide with more than 400 plants in operation. In the United States, there are more than 100 plants in operation, accounting for slightly less than 20% of our electric power production. It is important that even though there have been no new nuclear plants built in the last 15 years, we as a nation have been able to meet our growth in electric energy consumption primarily because of improvements in the efficiency and reliability of operation of nuclear power plants. They are now on-line, producing power, close to 90% of the time. The point is that despite all of the negative press, commercial reactors are operating very well and are an important part of our energy mix.

These reactor designs currently in use evolved from work primarily associated with what was done by the Navy. Westinghouse was a major contractor for the Navy, developing the pressurized water reactor that represents most of the plants in operation in the United States today. There are a few boiling water reactor designs, developed by General Electric, but they are in the minority. Sodium cooled reactors, such as EBR-I which besides producing the first electricity could create more fuel than it burned, never caught on. Water-cooled reactors were preferred by the Navy, so they got a leg up in the early days. There is a mature technology with these plants, there is not a shortage of fuel, and the technology has been deployed world wide. Water-cooled reactors do, however, create a great deal of spent fuel that we are just now beginning to grapple with. As the needs grow, different designs will take their place.

There are other designs scattered around the world, such as the Chernobyl type reactors that are a derivative from the Russian weapons program. Gas-cooled reactors operate in a few places. And there are a few operating sodium cooled reactors of a type that when eventually deployed, can greatly extend the available fuel supply.

It is worth commenting that many nuclear plants are becoming hugely profitable in the United States, primarily because they are becoming available at fire-sale prices. At least two operating companies have organized to buy them and operate them. The operating reactor at Three Mile Island (TMI) is a case in point. It cost several billion to construct, but was sold for about $30 million to a company called PepCo, a very competent operator of nuclear plants. We will see much more of this as individual utilities go out of the business and operating companies begin to take over, largely a result of deregulation of the electrical power industry. Many of the problems we know today developed because in the early history of nuclear power it was very fashionable for individual utilities to own a nuclear power plant, and many got into the business without the technical and management expertise to build and operate them. Witness the WPSS plants on the Columbia river in Washington state. This problem is now sorting itself out.

All of this experience, positive and negative, is laying the basis for what nuclear power will become. The future will be different than what we see today.

The world's population has reached 6 billion people and is projected to reach 10 billion in the next century. More than 30% live in poverty without access to electricity. Their life span averages less that 40 years. With access to even a little electricity and the benefits it brings, life span increases dramatically, to about 65 years. Significantly, the quality of life also increases dramatically.

Deregulation is spurring much innovation in the power generation business favoring small distributed generating sources that may well be suitable for many of these developing nations in the beginning of their expansion. Natural gas will grow in importance, particularly in the United States. But many countries either don't have access to gas, or the infrastructure to support it, or both. Electricity can be produced by many means, but only nuclear, coal and natural gas together have the potential to meet the needs of the next century, driven by the rapid growth of developing countries. To keep up, electricity production is expected to triple by the middle of the next century.

Some would say that we can't afford such growth. However, we cannot deny to the growing population of the world the benefits of a high standard of living. Just as important, it has been demonstrated over and over again, that countries with high standards of living have low population growth and less environmental degradation. So, besides improving the lives of individual people, such economic growth can also benefit the globe environmentally. That is really the key question, can we manage energy growth in a way that we can meet the needs of a hungry world, stabilize economics and protect the environment. This is a challenge worthy of us all.

Coal, in its present, cannot be a major part of that solution for a simple reason, global warming. The science to predict effects of CO_2 emission is still immature, and there is much uncertainty, but if the predictions are correct, it will have profound effects on climate, even at current levels of emissions. There is now no real question that global temperatures are increasing and that we will see the effects of human activity on global climate. What those affects will be and what to do about them are the present questions. There is talk of CO_2 sequestering but it is a technology far off. Natural gas can help, but only to a certain extent. We can talk about energy conservation, but that is for the developed nations, not the developing nations. We can talk about new technologies, solar, biomass, etc., and they have their place, but they will play only a part.

In spite of all its benefits, it is very unlikely that nuclear can fill the gap by itself, even if it is fully embraced. The required growth is phenomenal. For nuclear to provide even one-third of the carbon-free energy supply necessary to stabilize CO_2 levels would require building the equivalent of 100 large plants per year, starting now. If nuclear power is to play an essential part in addressing the greenhouse problem, slow steady growth will not be enough.

THE CHALLENGES FOR NUCLEAR POWER

Proliferation of Weapons Material

The first challenge for substantial growth of nuclear power is to prevent the proliferation of material that could be diverted to use in nuclear weapons. This is probably the greatest and most reasonable fear of those who strongly oppose nuclear power, especially its use in developing countries. It is such an emotional issue that there is talk about putting the genie back in the bottle. The nuclear genie cannot be put back into the bottle, so we will have to learn to control it. Nuclear has immense capability for good or for destruction. Frankly, our present problem is that nuclear power grew out of the weapons programs of Russia and the United States and we have ended up with technologies that are closely linked. We can do better. The first step is to bum down, to destroy, and to eliminate the excess weapons material that we currently have available. Burying it is not good enough. Let me say that again: burying it is not good enough. What we are talking about is not just the material produced for the weapons program, but the greater quantity of separated material produced in the civilian nuclear power programs. Burning the inventories down will greatly assist in management of the material that remains. Simply speaking, if the remaining material is locked up in reactor systems, it can't be used for weapons. Even more importantly, it can easily be monitored. What we need are reactor systems and associated fuel cycles that make it extremely difficult or impossible to divert material to weapons use. And we need the monitoring systems to make any attempt at diversion obvious to all.

Waste Management

Waste management is also an issue dominated by emotional considerations. The fundamental difficulty, as I have said, is that we are presently hung up on putting the genie back into the bottle. To this end, the permanent repository at Yucca Mountain in Nevada is intended to permanently lock material away, for a million years or more. This approach, of course, is hugely wasteful of a tremendously valuable resource, and probably can't be done to the standards being imposed anyway. Others outside our disciplines are beginning to understand this. There is currently an intense debate in Congress over employing interim storage instead of permanent disposal and transmutation of the waste, using reactors or accelerators is also being considered. There are international studies looking at the same questions. There are also international studies looking at improved methods of fuel management that include recycle. One thing is clear, burning less than 1% of the available fuel and discarding the rest as we are doing today is bound to create a huge waste problem. It is simply better to recycle, as we do with so many of our other products. This will come. It is a question of time and the right technology. I would emphasize that it is recycle for the purpose of burning down the inventory of material, not creating more. To this end, the Russians and the Japanese are entering into an agreement for fueling a Russian sodium-cooled reactor with weapons plutonium, recycling the fuel in a proliferation resistant system using electrorefining. We can expect other international initiatives to develop, such as deep burn reactors and other concepts. We also should be exploring long life reactor cores that produce and burn their own fuel without need for external separation of material.

Economics

Any power source must make sense in a competitive market. Nuclear power suffers from the fact that each plant built in this country was one of a kind, with only a few exceptions. Further, each one had to be a Cadillac to satisfy safety requirements, requirements which were continually being changed.

The automobile industry could not succeed on a broad scale until it moved away from hand building individual luxury cars and moved toward mass production of vehicles that comply with known and excepted standards. The same applies to nuclear plants. The cars of today are vastly superior in every respect, especially safety, to those that preceded them, hand built or not. They are a great value.

The same must happen with nuclear power. Smaller, modular plants produced in factories are part of the answer. Standardization of a few designs is another part of the answer. Surprisingly, cheaper and simpler can also mean safer.

Safety

The enemy of safety is complexity. Our nuclear plants have become increasingly complex, in part, ironically, because of the addition of many safety systems. It is always more straightforward to engineer a safety fix with the addition of a new system. Rather, I think we need to return to the fundamental design and take advantage of the inherent physics to ensure that it will respond safely. It is possible to design an aircraft that can glide after the engines are lost, and to stall at such a slow speed that it can be landed safely on rough terrain. Likewise, it is possible to design a reactor that will coast down in power on its own after losing all electrical power, without requiring active safety systems. This concept was proved at Argonne in 1986 when all safety systems and cooling systems were disabled at full power on EBR-II. Because this reactor employed inherent safety in its design, it coasted down safely and never over heated. Such features are being incorporated into the newest designs. Unfortunately, they are not being built in this country so we cannot directly see their benefits. One huge benefit is that their safety systems can then be simplified, and costs reduced. This is a field of research and development with great promise for the future.

Perhaps, though, the biggest challenge in the meantime is avoiding accidents. Another accident on the scale of Chernobyl, or continuing accidents like the criticality in Japan, would have a devastating impact on the nuclear industry. Yet today, there are 26 of the oldest Soviet designed power plants in operation; 14 of the RBMks and a dozen of the VVER-440-230s. They have no containment vessels and inadequate to non-existent emergency core cooling systems. Genuine safety risks exist elsewhere where rapid growth is foreseen without the infrastructure to support it. The United States must provide the leadership to ensure that these problems are addressed.

THE FUTURE FOR NUCLEAR POWER

Advanced Reactor Development

We are then confronted with the challenges of proliferation, waste, economics and safety. These are not new challenges. We addressed them at Argonne in the early 80s with the development of the Integral Fast Reactor (IFR) program, and created a great deal of excitement in the process. We demonstrated that a proliferation resistant fuel cycle, that is transparent for those who would monitor it, could be developed. We demonstrated that fuel could be recycled to the reactor, so that fuel and fission products could be burned, not added to the waste and buried. We demonstrated that we could simplify the design, greatly improving the economics. And we demonstrated that safety could be assured while greatly simplifying reactor design. In short, the IFR program was a great technical success. It made significant progress in both defining the questions to be asked, and in answering them. Even though the IFR was terminated for political reasons in 1994, it has laid the groundwork for important work in the future. Much of this work is happening in the international arena.

There is much being done in the international arena. Unfortunately, much of it has to do with correcting the mistakes of the past, cleaning up contamination from many sites associated with the weapons programs and properly managing material and reactors that remain.

It is important that the United States maintain its expertise if it is to maintain international leadership. Problems will arise and it is important that we are able to deal with them. Developing nations will turn to nuclear power to improve the lives of their people, and it is important that we are at the table to assure that this is done in a safe and secure manner. The only way for other nations to respect the United States as a leader in policy is to be a leader in the technology.

Fortunately, there are important initiatives emerging. Congress has funded the Nuclear Engineering Research Institute (NERI) at $19 million, a relatively low level, but an important beginning. The money funds a number of nascent, innovative research initiatives from universities and national laboratories to develop new approaches to nuclear reactor design, among other things. Let me describe one such initiative. There is being developed a water-cooled reactor with a core that is envisioned to operate for 14 years without refueling. At 14 years, the whole core will be replaced. Because there is no need for refueling, there is no need for a refueling system and the cost it entails. Because there is no movement of fuel, there is no risk of diversion of material.

In addition, the design will maximize thc inherently safe response to upsets. For example, the core can be cooled by natural convection only, without need for pumps or electric power. Such simplification can enhance safcty and reduce cost.

Probably the best demonstration of what can be achieved was with the sodium cooled reactor, EBR-II. In 1986, two landmark demonstration tests were conducted before an international audience. The reactor was subjected to the two worst events that can befall a power reactor.

In the first, the reactor was brought to full power, the automatic shutdown system was disabled and all electric power to the reactor cooling systems was removed. The coolant flow to the core immediately began to decrease, the reactor temperature started to rise, but instead of melting the core, it shut itself down without damage. It glided to a safe landing where it remained.

In the second test, the reactor was again brought to full power, the automatic shutdown system was disengaged and all power was cut to the pumps that reject heat from the reactor. The response was even more benign in this test than in the first. Again, the reactor shut itself down with no damage.

Such designs are possible and have captured the imagination of an international audience. In the example mentioned for a light water reactor design, the French and the Japanese are participating. Another reactor design, a pebble-bed gas cooled reactor, has attracted an even broader international audience.

CONCLUSION

We can all be thankful for nuclear power, for it may well be essential to the long term survival of civilization. Within the seeds of its potential for great good, are also the seeds for great harm. We must ensure that it is applied for great good. What is not in question is whether we can live without it, we cannot.

United States leadership is crucial in determining how this technology is developed and applied. The size and capability of the United States technical community is decreasing, a trend that cannot be allowed to continue. It is my belief that in the future, the need, the vision and the confidence in nuclear power will be restored, but only if we address the immediate challenges before us. It is a national challenge worthy of the best people this nation has to offer.