Dangerous Anthropogenic Interference*

A Discussion of Humanity's Faustian Climate Bargain and the Payments Coming Due

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I have been told by a high government official that I should not talk about "dangerous anthropogenic interference" with climate, because we do not know how much humans are changing the Earth's climate or how much change is "dangerous". Actually, we know quite a lot. Natural regional climate fluctuations remain larger today than human-made effects such as global warming. But data show that we are at a point where human effects are competing with nature and the balance is shifting.

Ominously, the data show that human effects have been minimized by a Faustian bargain: global warming effects have been mitigated by air pollutants that reduce the amount of sunlight reaching the Earth's surface. This Faustian bargain has a time limit, and the payment is now coming due.

Actions that would alleviate human distortions of nature are not only feasible but make sense for other reasons, including our economic well-being and national security. However, our present plan in the United States is to wait another decade before re-examining the climate change matter. Delay of another decade, I argue, is a colossal risk.

The scientific method, exemplified to me as a student by Prof. James Van Allen's Department of Physics and Astronomy, has the potential to aid the public and decision-makers in addressing the global warming issue in ways that have multiple benefits to our environmental and economic well being. So far, this process has been hampered, as the global warming story reveals various dangerous interferences with the scientific process.

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The opinions and interpretations that I express today are my personal views. I am a government employee, but I am on leave today, I travel here at my expense, and I speak as a private citizen, a resident now of Kintnersville, Pennsylvania. I hope to convince you that I am knowledgeable about climate change and that the information I provide warrants your consideration, but the views that I present have no official sanction.

My talk will be in two parts. First, I will describe the global warming problem from my perspective, looking at the Earth as a planet, a viewpoint that derives in part from my training here in Physics and Astronomy. I use charts mainly from my own papers for practical reasons, but, except for some details that I will discuss, my conclusions are consistent with those of the IPCC, the United Nations Intergovernmental Panel on Climate Change, which involves thousands of scientists. Inferences about human impact on climate and prospects for continued climate change are a consensus of most of the relevant scientific community.

The second part of my talk will concern practical implications of climate change, and attempts to communicate it. I spoke twice to the group that the President assigned to examine this topic, the group consisting of six cabinet members, the administrator of EPA, the National Security Advisor, and the Vice President, who was the chairman. Appropriately, this is the same group that has helped set the nation's energy policy.

My conclusion is that we, in the United States, are on a dangerous course in our climate and energy policies. I have written a paper with my student team in which we try to explain this situation more clearly and communicate the opportunities that we have to reduce the climate change danger while achieving other benefits. I will summarize that paper in the second part of my talk. That paper and this talk are available on the web site of Columbia University's Earth Institute at http://www.Columbia.edu/~jeh1/

1. Prof. Van Allen's Department of Physics and Astronomy.

First I would like to express my appreciation to the State of Iowa, the University, and especially Prof. Van Allen and his Department of Physics and Astronomy, for the opportunities that they generously provided. In my old age I recognize the unusual opportunities that I had here.

Figure 1. (a) Parents and older sisters. (b) With four older sisters and friend.

I was really lucky to be born in Iowa and to live here my first 25 years. (Don't worry, I have only one chart on this! But it has two parts so I can show my parents.) I was born on a farm, literally in a farmhouse, in Charter Oak township, in western Iowa. I was treated very well, at least for a while, because I was the first boy (you can see that I was well fed). Our father had only an 8^{th} grade education, but in those days in Iowa, and I hope it is still true, it was not difficult to work your way through college. My good fortune was to come to this university, and to find and be infused with the exciting atmosphere of discovery in Prof. Van Allen's department, where I learned how the scientific process works.

The impact on me occurred in spite of myself. I was so shy and unconfident that, when I had the opportunity to take a course under Prof. Van Allen, I avoided it, because I didn't want him to realize how ignorant I was. But despite sitting in the back of the classes, I soaked up things pretty well, and I believe that I was one of the first two students to take and pass the physics graduate qualifying exam while being an undergraduate.

Although Prof. Van Allen was not my official advisor, he suggested that I look at microwave and radiowave observations of Venus that implied the planet was very hot. In those days, to qualify for a Ph.D., among other things a student needed to make an "original proposition" and defend this before a committee of professors, to show that he or she understood scientific methods. So, contrary to the likely interpretation that the surface of Venus was warm because it had a thick atmosphere of greenhouse gases, as was argued by Carl Sagan, Jim Pollack and other scientists, I made a proposition that Venus might be kept warm by the dusty haze that seemed to fill its atmosphere.

2. The Goldilock's Planets.

Well, that made a good proposition, but when spacecraft arrived at Venus they confirmed that, as Sagan and Pollack suggested, it was primarily a thick atmosphere of carbon dioxide that kept Venus so hot. The haze of Venus turned out to be sulfuric acid, which contributes to the temperature on Venus, but the primary cause of the high temperature is the carbon dioxide.

Figure 2. The Goldilocks Planets.

This has relevance to the Earth's climate. If we compare Venus, Earth and Mars, we find the Goldilocks situation. One is much too hot, one is much too cold, and one is just right. The reason Mars is cold is that it has only a thin atmosphere of CO_2, which warms it by only a few degrees above the temperature that it would otherwise have, given the amount of sunlight that it absorbs. Venus has a thick atmosphere that warms it by a few hundred degrees. The Earth has enough greenhouse gases to warm it by a few tens of degrees, enough to make it a nice place to live. The way this works is: greenhouse gases are transparent to sunlight, which passes through the atmosphere and heats the planet's surface, but the gases partially block heat radiation, making it more difficult for heat to escape. Like a blanket, they keep the surface warm.

The other planets are an exciting subject, but years later, in the 1970s, when it was first realized that there were several different greenhouse gases that humans were causing to increase in the Earth's atmosphere, I became captivated by the Earth's greenhouse problem. A planet that is changing before our eyes is even more interesting. And what happens on Earth is important to billions of people, to wildlife, and the environment in general.

3. How Science Works.

Before I talk about climate, let me say one more thing about the Department. The scientific method is not learned by rote, from a textbook, or by coming to class and having the professor fill you up with knowledge, like pouring liquid from a pitcher into your head. It's more something learned by osmosis, by working in a scientific environment. I remember one time Prof. Van Allen gave an informal seminar, writing some numbers on the blackboard. I didn't fully understand it; it related to energies of particles measured in an ongoing spacecraft experiment. He didn't say we discovered "this" and it means "that". Instead he discussed possible interpretations, pros and cons, and what the limitations of the data were. It left a lasting impression on me about how research works.

Figure 3. Feynman Quotation. (see http://www.giss.nasa.gov/edu/gwdebate)

My favorite quotation about "how science works" is by Richard Feynman: "The only way to have real success in science … is to describe the evidence very carefully without regard to the way you feel it should be. If you have a theory, you must try to explain what's good about it and what's bad about it equally. In science you learn a sort of standard integrity and honesty."

It's a simple but profound statement. If you do not follow this rigorously, you can easily fool yourself. I will return to this statement later.

4. Climate Variability: Does God Play Dice?

Let's consider climate and climate change. Weather, and climate, which is the average weather, are always changing. The atmosphere and the ocean are coupled fluids that are always sloshing about.

Figure 4. Temperature anomalies in 2004, relative to 1951-1980 mean (reference 1).

For example these are maps of temperature anomalies this year. The anomalies are the deviations from the normal temperature for each month. The normal is defined as the 30-year average, 1951-1980. That's the period the National Weather Service used to define normal climatology in the 1980s, when global warming became a public issue.

Yellows and reds are warmer than the 30-year normal. Blues are colder than normal. The patterns move around from month to month. Notice that the magnitude of these regional anomalies is as much as 5 to 6 degrees Celsius, which is about 10 degrees Fahrenheit.

The number in the upper right corner of each map is the global average anomaly. Every month is warmer than normal, that is warmer than the 1951-1980 average for that month, typically by about half a degree Celsius, which is about 1 degree Fahrenheit. This "global warming" is much smaller than the month-to-month local temperature fluctuations. But the global average warming is just reaching the point where it will be noticeable and begin to have practical implications.

About 15 years ago I wrote a paper that said by the beginning of the 21st century the probability that seasonal mean temperature would be in the warm category, defined by the warmest 33% of the seasons in the period 1951-1980, would increase to about 60-70%. In other words the climate dice would be loaded. When the dice are rolled, they still may come up colder than normal, but not as frequently as they used to. These odds refer to the seasonal (3 month) average temperature, which reduces the monthly noise. But before drawing any conclusions about whether the dice are loaded, you need to roll them at least several times.

Look at June this year. It was cooler than normal in the Midwest. July continued unusually cool. And August was even colder than normal. So the summer mean, June-July-August, was extremely unusual, probably cool enough to convince a lot of people in Iowa that global warming must be a lot of baloney. However, if you look at such global maps for the past several years, you will see that the dice do seem to be loaded.

Loaded dice don't mean that you win every time you roll. You can still get snake eyes, as happened last summer, but the odds are against it. I would estimate that in the next 10 seasons, you will probably get 6 or 7 in the warmer than normal category, 1 or 2 in the unusually cool category, and 2 or 3 in the normal range. Maybe I will check with you 2½ years in the future, to see how this experiment came out.

Figure 5. Global mean temperature change, based on meteorological stations before 1900 and stations plus sea surface temperatures after 1900 (reference 1).

If we average over the whole world, global warming is more apparent. The warming is about 6 or 7 tenths of a degree Celsius in the past century, a bit more than 1 degree Fahrenheit. Most of the warming is in the past 30 years.

You may be asking: why do we care about global warming if it is small compared to local natural fluctuations? It's a good question. In order to answer it, we need some understanding of climate change, what the practical impacts of climate change are, and a means to predict the magnitude of future human-made climate change. So let's defer that question until we have considered the causes of climate change.

5. Forcings and Chaos: What Determines Climate Change?

Climate is chaotic, it fluctuates like the weather, without any forcing. But, in addition, the long-term average climate can also shift systematically in response to forcings. If we move the Earth closer to the sun, for example, we can be sure that the Earth will become warmer. Solar irradiance is one of the forcing agents that affects climate.

To analyze climate change, we need to know: (1) what are the significant climate forcing agents, (2) how sensitive is the Earth's climate to a forcing, and (3) how long does it take for the Earth to respond to a change in the forcings?

We measure forcings in Watts per square meter. The sunlight absorbed by the Earth, averaged over the Earth, is 240 W/m^2. So if the sun became 1% brighter, that would be a positive forcing of 2.4 W/m^2.

Figure 6. Climate forcing agents in the Industrial Era.

What are the important climate forcings? They can include external input to the system, such as changes of sunlight, or changes within the atmosphere or changes on the planet's surface. We have been measuring the sunlight, and the atmosphere, and the surface, for the past few decades, and we have been measuring some of these quantities for the past century. This bar graph shows estimated changes of the climate forcings during the industrial era, since 1850.

The strong positive forcings, totaling about 3 Watts, are the human-made greenhouse gases, carbon dioxide, methane, chlorofluorocarbons. The primary negative forcing is caused by human-made aerosols, which are fine particles in the air, especially sulfuric acid or sulfates (like on Venus), which is mainly a product of burning fossil fuels containing sulfates. Aerosols reflect sunlight, so they cause cooling, except one aerosol, black carbon or soot, which absorbs sunlight and causes warming. Aerosols also act as condensation nuclei for cloud drops, causing clouds to reflect more sunlight, thus having a cooling effect.

The sun's irradiance has been measured accurately for 25 years, revealing a change of about 0.1% over a solar cycle, and weak evidence of a long-term change. From those data and longer observations of features on the sun, it is inferred that the sun probably brightened slightly over the past two centuries, causing a forcing of a few tenths of 1 Watt (per square meter).

6. Two Watts per Square Meter: Is That Important?

So it seems that human forcings are the dominant forcings. For the moment, let's accept these measurements and estimates at face value. They yield a net forcing a bit less than 2 W/m^2.

Figure 7a & 7b. Sophie and Connor demonstrating 2 Watts of forcing.

(A) Sophie, my grand-daughter is explaining to her well-fed brother Connor, the concept of climate forcings using 1-Watt Christmas tree bulbs. (B) Even though Connor is only 5 months old, you can see in his eyes that he gets it: it is 2 Watts. The human climate forcing is as if we had placed two of these miniature bulbs over every square meter of the Earth's surface. So. Is that amount of energy important?

To answer that, we need to know: how sensitive is the climate to a forcing? Climate models can address this question, but the most reliable data that we have comes from the history of the Earth.

Figure 8. Vostok (Russian base in central Antarctica) temperature for past 400,000 years (reference 3).

Figure 8 shows the estimated temperature of the Earth during the past 400,000 years. This is obtained from an ice core drilled through the ice sheet covering Antarctica, which was laid down by snowfall year-by-year that compressed into ice. The isotopic composition of the snow records the local temperature at the time the snow fell. Long-term temperature variations in Antarctica are typically twice as large as global mean temperature change. The scale for global temperature is given on the right side.

The Earth has been in a warm interglacial period for the past 12,000 years. We can compare this warm period with the last major ice age, which peaked about 20,000 years ago.

Figure 9. Vostok carbon dioxide, methane, and temperature record for the past 400,000 years.

Figure 9 shows that, as the climate changed, so did atmospheric composition, recorded by bubbles of air trapped as the ice sheet built up year-by-year. This is the carbon dioxide, methane and temperature as a function of time. These swings from glacial to interglacial conditions are driven by perturbations of the Earth's orbit caused mainly by Jupiter and Saturn, because they are so massive, and Venus, because it comes close. The resulting seasonal variations of sunlight affect the building and decay of ice sheets as well as the uptake and release of greenhouse gases by the ocean and by vegetation. During the last ice age an ice sheet covered Canada, reaching down as far as Iowa, incidentally pushing a gift of black soil from Minnesota to Iowa.

7. A Message from the Last Ice Age

As shown in Figure 10, we know accurately the mechanisms that kept the ice age colder than today. The reduced CO_2, CH_4 and N_2O caused a forcing of about 2½ Watts per square meter. The surface was also different. The ice sheets covering parts of North America, Europe, and Asia reflected more sunlight, and the vegetation distributions were different and sea level was 400 feet lower. Altogether the forcing totaled about 6½ W/m^2. This forcing maintained a planet 5°C colder, implying a climate sensitivity of ¾°C per W/m^2.

Figure 10. Ice age climate forcings imply a climate forcing of ¾°C per W/m^2.

Global climate models once gave a wide range of estimates for climate sensitivity. Recently the models seem to be zeroing in on a sensitivity of about ¾°C per W/m^2, the same as the empirical value, which is comforting. However, the empirical evidence from the Earth's history is more accurate and reliable, because we can be sure that all the important processes and feedbacks are included in the real world data.

Recall that we estimate climate forcing change in the past century as about 1.6 W/m^2 (Figure 6) with a large uncertainty. If the sensitivity is ¾°C per Watt, the eventual warming should be 1.2°C. Observed global warming is about 0.7°C. Is there a discrepancy, or is this difference caused by the slow response time of the climate system? That's where a global atmosphere-ocean climate model becomes very useful, because it let's us realistically simulate ocean heat uptake and thus the temporal response of climate to forcing agents.

7. Climate Change in the Industrial Era

Figure 11. Estimated climate forcings during the past 150 years (reference 5).

Figure 11 shows estimated climate forcings for the past century. The greenhouse gas curve is known accurately, because most greenhouse gases are well-mixed in the atmosphere, so measurements are only needed at one place. Stratospheric aerosols from volcanoes cause the irregular negative forcing, which has a cooling effect. It is also known accurately, at least in the past 50 years. The largest uncertainties are tropospheric aerosols and their indirect effect on clouds. Tropospheric aerosol forcings are based in part on aerosol transport models, which are used to fill in for missing observations. Some of the smaller forcings are known well, while others are not.

Figure 12. Observed and simulated global surface temperature change for forcings of Figure 11. The five model runs differ in initial ocean and atmosphere conditions, and thus follow their own chaotic paths (reference 5).

If we accept these climate forcings at face value and use them to drive a global climate model, what do we get? Results are shown in Figure 12. The model does a good job of reproducing global temperature change over the past century. This does not provide a unique interpretation of the data. If we used a model with smaller climate sensitivity but a larger climate forcing, or if we had used a larger sensitivity but a smaller forcing, we may also get good agreement. But recall that climate sensitivity is constrained by paleoclimate data. There is not a great deal of flexibility in climate sensitivity.

Figure 13. Global climate simulations driven by forcings of Figure 11 (reference 5).

The global warming is about seven tenths of a degree Celsius. So where is the other half degree of the expected 1.2°C warming that we discussed earlier? We can see the answer if we look at the model in a little more detail. Figure 13 shows that the model agrees with global tropospheric and stratospheric temperature change, although the observations of these upper air quantities are for a shorter period.

8. The Critical Data: The Planetary Energy Imbalance

A critical piece of data is the energy imbalance of the planet. If our story is correct, if the Earth is being driven to a warmer climate by positive forcings, there should be less energy going out from the planet, compared to the energy coming in. That's how the greenhouse effect works, the gases block energy from going out. Of course, when the planet warms up, it restores energy balance, but the ocean takes at least several decades to warm up, and by that time more gases have been added, so there is a continuous imbalance. That planetary energy imbalance is a direct measure of the climate forcing that the Earth has not yet responded to.

According to our model, if the forcings that we have assumed are correct, the Earth must now be out of balance by about ¾ ± ¼ W/m^2. That's the graph in the upper left of Figure 13. And because the heat capacity of the atmosphere is negligible, the heat going into the ocean should also be about ¾ ± ¼ W/m^2; that's the second graph on the left. This imbalance implies that there is additional global warming in the pipeline. ¾ Watt implies about ½°C additional warming is in the pipeline, without any further increase in greenhouse gases.

Several years ago I was asked "what are the three most important measurements" to improve understanding of global warming. I said "ocean heat storage, ocean heat storage and ocean heat storage", because the rate at which the ocean is increasing its heat content is such a fundamental quantity. It is a direct measure of the net climate forcing now operating on the world.

Now we are beginning to get such data. A few years ago, Syd Levitus and colleagues at NOAA published analyses of millions of ocean temperature measurements taken between about 1950 and 1990. They inferred that the ocean warmed over that period by an amount consistent with climate models such as the one shown here. However, the period covered did not include the past 10 years, when we believe the energy imbalance is largest and can be quantified most precisely.

The most valuable data would be accurate measurements of the current rate of change of ocean heat content. That would tell us if the planet is indeed out of energy balance. This would be a measure of what forcing is now acting on the planet. Just such a check is now possible for the period 1993-2003, based on comprehensive data that has just become available for that period (Willis et al., 2004, reference 11).

Figure 14. Ocean heat content change between 1993 and 2003 in top 750 meters of the world ocean. Observations from reference 11. Climate model the same as in previous two figures, driven by climate forcings in Figure 11.

In a paper in press Willis et al. (reference 11) show that between 1993 and 2003 the heat content of the upper 750 meters of ocean increased at a rate equivalent to an average global heating rate of 0.60 ± 0.10 W/m^2. The average planetary energy imbalance in our climate model simulations for 1993-2003 (Figure 12) is 0.80 ± 0.06 W/m^2, where the standard deviation refers to the five model simulations. However, in the five coupled atmosphere-ocean climate simulations 82 ± 10% (standard deviation) of the increased ocean heat content is stored in the upper 750 meters of the ocean during 1993-2003, with the remaining 18% stored in the deeper ocean. We infer not only that the planet is substantially out of energy balance with space, but in close agreement with the model.

Although it is not inconceivable that such a decade-long energy imbalance could arise as a fluke, e.g., from some sudden change in ocean circulation, that seems unlikely and I know of no evidence supporting such an ocean fluctuation.

The confirmation that the Earth is out of energy balance has broad implications. First it confirms that our net climate forcing estimate is reasonably accurate. Second, it confirms that additional global warming is in the pipeline. The planet must warm up another ½°C to restore energy balance with space.

9. Dangerous Anthropogenic Interference

What constitutes dangerous anthropogenic interference with climate? Nobody knows for sure. But let's look at how our changes of the past century compare with the history of the Earth. Figure 15 compares atmospheric CO_2 in the past 150 years (the small segment on the right) with CO_2 amounts in the previous 400,000 years. CO_2 is now far above any level in the past hundreds of thousands of years. The methane change is even more dramatic. This graph alone should make us talk about the possibility of dangerous anthropogenic interference.

Figure 15. CO_2, CH_4 and temperature records inferred from Antarctic ice core and recent in situ measurements (reference 6). Time scale after 1850 is expanded to allow changes of the past century to be seen. The indicated global temperature anomaly, relative to the 1880-1899 mean, is estimated to be half of the Antarctic temperature anomaly.

Climate has not fully responded to these greenhouse gas forcings, in part because of the thermal inertia of the ocean, and in part because the greenhouse forcing is partially counterbalanced by aerosol cooling.

The bottom curve is the temperature. The Earth has warmed in the past century. As well as we can estimate, current global temperature is just now rising through the peak level of the current interglacial period, previously attained about 10,000 years ago. Some of the earlier interglacial periods were slightly warmer than the current one, perhaps as much as 1°C warmer globally, and 2-3°C warmer at the South Pole. In the warmer interglacial periods sea level is estimated to have been 5-6 meters higher, but it is difficult to verify changes of that amount.

It is clearer if we go back to the Middle Pliocene, about 3 million years ago. Global temperature at that time is estimated to have been 2 to 2½°C warmer than today, and sea level was 25 meters higher. It was a very different planet than the one we live on. The ice sheets on Greenland and Antarctica must have been much smaller.

In my opinion, the effect of global warming on the ice sheets, and thus on sea level, will determine the amount of global warming that constitutes dangerous anthropogenic interference. That phrase arises from the Framework Convention on Climate Change of 1991, in which the United States and practically all other countries agreed to work to stabilize atmospheric composition at a level that avoids "dangerous anthropogenic interference" with climate.

This is one topic on which I disagree with IPCC (chapter 19, reference 12), which leaves the impression that we need to begin to worry if global warming reaches 2-3°C. They are basing that evaluation on models that include limited processes. In the case of ice sheets, there is a common presumption that it takes millennia for ice sheets to respond to a change of climate.

Figure 16. Moulin photo: What determines "dangerous anthropogenic interference"? (Roger Braithwaite photo, from reference 2).

The history of the Earth shows that, indeed, the building of ice sheets requires many millennia. Building an ice sheet is a dry process. The rate of ice sheet growth is limited at maximum to the annual snowfall rate. But disintegration of an ice sheet is a wet process, which can be explosively rapid. This photo shows a moulin on the Greenland ice sheet, a hole a mile deep that goes to the base of the ice sheet, delivering summer meltwater that lubricates the bottom of the ice sheet.

Figure 17. The area with summer snowmelt on Greenland in 1992 and 2002 (credit).

Summer melt is normal on the fringes of Greenland. However, with global warming the area of Greenland that is undergoing summer melt is increasing. This image compares the area that underwent melt in 1992 to the area in 2002, which is greatly expanded. The rate of expansion may be slightly exaggerated here, because 1992 was cooled by Pinatubo volcanic aerosols. However, there is a real and substantial trend toward greater and greater areas of Greenland undergoing summer snow melt.

Figure 18. Ice discharge from Greenland. Flow velocity from Jakobshavn ice stream increased ~40 in past three years (Waleed Abdalati, AGU presntation; photo courtesy of Konrad Steffen).

And this is having an impact on the ice sheet. A number of ice streams, the parts of the ice sheet that move most rapidly, are speeding up and delivering more icebergs to the ocean. This is important because energy to melt the ice is drawn from the huge heat reservoir in the ocean. And energy used to melt ice is re-supplied, because the cooling of the ocean surface increases the planetary energy imbalance, thus increasing the flux of heat into the ocean.

For this reason, ice sheets can disintegrate rapidly once the process is well underway. About 14,000 years ago, during the transition from the last ice age to the current interglacial period, there was a 400 year period in which sea level rose 20 meters. That's one meter every 20 years. Sea level change and it's relevance to setting the level of global warming constituting "dangerous anthropogenic interference" is discussed more in an editorial in press in Climatic Change (reference 6). I argue there that sea level rise of two meters or more, enough to submerge some island nations, much of Bangladesh, the Nile Delta, and parts of Louisiana and Florida, constitutes dangerous anthropogenic interference. In turn, I argue from the Earth's history, that a reasonable limit on sea level change implies that we should aim to keep further global warming from exceeding approximately 1°C.

Figure 19. Precipitation changes with increasing CO_2 and "all forcings" in 2000 (reference 7).

10. Regional Climate: Droughts and Floods

Of course, you may not be too worried about sea level in Iowa. I wish that I could tell you the regional climate impacts of global warming, but models are not very trustworthy for that. I will venture one prediction, however. Here is the change in precipitation that we find in our climate model as greenhouse gases increase. As CO_2 goes from 1.5 times the pre-industrial amount to 2 times and four times, the precipitation increases in tropics and decreases in the subtropics. This makes sense as the Hadley circulation intensifies, with rising air in the tropics and sinking in the subtropics. Today's greenhouse gases are equivalent to 1.5 times CO_2 and we see in the final panel that even when the other nine forcings are added in the tendencies survive for increases in the tropics and decreases in the subtropics.

The practical implication of this seems to be that the Southwest United States and the Mediterranean and the Middle East become drier and the Eastern United States becomes wetter. This is consistent with a recent paper of Cook et al. (12), who find in the paleoclimate history that the western United States tended to have more extreme drought when the planet was warmer. Iowa seems to fall in the border region between the west getting drier and the east getting wetter. So I have to chicken-out -- I can't hazard a prediction on what global warming means for precipitation in Iowa without more information.

11. Faustian Bargain

I must summarize further science succinctly.

Greenhouse gases are only part of the climate change story. There are other climate forcings. The most important 'other' climate forcing is that due to aerosols, small particles in the air. I showed in two previous graphs (Figures 6 and 11) that climate forcing by aerosols is about half as large as that by greenhouse gases, but the aerosol forcing is negative and causes cooling.

The industrial revolution not only produces gases, it also kicks up dust, acids and black soot particles. These little particles have reduced global warming by at least 50% from what it would otherwise have been. They have allowed us to enjoy the fruits of industrialization with only moderate global warming. But these aerosols do not come without cost, and the big payment they demand is now coming due.

Figure 20. The Faustian bargain. Humans have enjoyed the fruits of the industrial revolution and avoided a large cost in climate change, as aerosol cooling has mitigated greenhouse warming. Payment comes due when humanity realizes that it cannot tolerate the further exponential growth of air pollution that would be needed for continued mitigation of global warming.

Andy Lacis, who is also a graduate of the Physics and Astronomy Department, and I wrote a paper in Nature in 1990 in which we described this masking of greenhouse warming by aerosol cooling as a Faustian bargain, because it can only be maintained by putting ever larger amounts of these particles in the air. And humans are realizing that they do not like these dirty little aerosols. They kill more than a million people a year world-wide. About 50,000 per year in the United States and an order of magnitude more in India and China. These small particles enter the lungs, penetrate human tissue deeply, and even enter the bloodstream. They are a major reason for increasing asthma and other respiratory and cardio-vascular problems.

Aerosol pollution is being addressed now in the United States and Europe and undoubtedly it will be addressed in developing countries such as India and China. As aerosols are reduced, unless we have a strategy that deals effectively with the climate problem, global warming is going to markedly accelerate.

Full discussion of this topic is impractical here. But I want to point out that there are ways to minimize the payment due and optimize the consequences, provided that we put special emphasis on reducing certain air pollutants such as black carbon, ozone and its precursors, especially methane. Indeed, substantial benefits for human health and agricultural productivity would occur if these pollutants were reduced.

12. Scenarios for Carbon Dioxide

The most difficult task, and the one that we cannot afford to put off any longer, is to slow carbon dioxide emissions. Figure 21 shows projections of global temperature for the 21st century based on IPCC business-as-usual scenarios that cover a wide range of assumptions about economic growth and fuel choices, but do not include deliberate reductions of emissions to slow climate change. The alternative scenario is one in which the rate of CO_2 emissions levels out in the first decade of the century and declines significantly before mid-century.

Figure 21. Global surface temperature simulations extended through 21^{st} century (reference 5).

With the alternative scenario, added global warming remains under 1°C. Any of the business-as-usual scenarios yield global warming much more than 1°C and take the planet to levels that have not existed in hundreds of thousands, probably millions of years. It is implausible to assume that we could avoid dangerous anthropogenic interference if we follow the business-as-usual scenarios.

Let's look at how we are doing on CO_2. The blue line in the top panel of Figure 22 is the observed annual growth of CO_2 in the air. Because of the large year-to-year variability, it is not immediately obvious whether the world is more on the course of IPCC business-as-usual scenario or the alternative scenario. However, if we look at the global fossil fuel CO_2 emissions in the lower left we see that emissions are continuing to rise rapidly. In the lower right we see that the fraction of the emissions that stays in the air continues to fluctuate about the 60% level.

Figure 22. (A) Annual growth of atmospheric CO_2 based on measurements through 2003 and on scenarios of IPCC (reference 8) and Hansen and Sato (reference 9). Fossil fuel emissions are continuing to grow as shown by the top curve in (B). The average fraction of emissions that remains airborne (C) continues to be about 60%, implying that the underlying CO_2 growth rate is now 1.9 ppm/year, closer to the IPCC (2001; reference 8) scenarios than to the "Alternative Scenario" (reference 10).

The product of 60% and current CO_2 emissions yields 1.9 ppm CO_2 per year as the current growth rate of atmospheric CO_2. Therefore, the underlying CO_2 growth rate is closer to the IPCC scenarios than to the alternative scenario. The alternative scenario has the 21^{st} century starting with the CO_2 growth rate of the late 1990s, 1.7 ppm per year, and decreasing by mid-century to 1.3 ppm per year, thus an average of 1.5 ppm per year, which yields a forcing of 1 W/m^2. The current CO_2 emissions are not only above that rate, but the derivative has the wrong sign. The annual CO_2 growth is continuing to accelerate, not level out and decline.

If we ignore the climate issue for another decade and continue to build more infrastructure to produce more CO_2 emissions, the CO_2 annual growth in a decade will be at a still higher level than 1.9 ppm. We will have passed the point, given the increased CO_2 producing infrastructure in place, beyond which it becomes impractical to bring atmospheric CO_2 growth rates down to the level of the alternative scenario in this half century. I remind you that the alternative scenario is approximately the maximum growth rate for CO_2 that would keep additional global warming from exceeding 1°C.

13. On the Road to Climate Stability: The Parable of the Secretary

I'm sorry to rush through the science. A clearer discussion of this material is perhaps that published in the March issue of Scientific American, which is available on the same web site that I provide here.

Now I turn to interactions that I have had with policy-makers. As I mentioned earlier I spoke twice to the cabinet level group that addressed the climate change matter, chaired by the Vice President. At the first meeting the Secretary of the Treasury Paul O'Neill said that he had spoken with the President the day before the meeting and the President told him that he wanted the United States to take a leadership role in addressing the issue of climate change and to find ways to most effectively address the matter.

Figure. 23. A-Team paper available at http://www.

In the three and one-half years since then, many things have become clearer. The story is told as best as I can by the article "On the Road to Climate Stability", which is available on the web as indicated. I also call it "The Parable of the Secretary". As a principal character in this story I had in mind a composite of Paul O'Neill, because he seemed so interested in the climate change topic, and Colin Powell, because of its relevance to his job. O'Neill is out of the government now, so it might be possible to check with him regarding the realism of the story.

Ten years ago Carolyn Harris, a former high school teacher, and I started an education outreach program, the Institute on Climate and Planets, involving high school students, high school teachers, as well college students and professors. The notion was inspired by my experience in Prof Van Allen's Department, the notion being that you learn science best by osmosis working with scientists on problems at the top of their research agenda. We divided the students and teachers into several teams, each headed by researchers in our laboratory.

My team was called the A-Team, for Alternative Scenario. The assignment that I gave the A-Team was a task the way I imagined it would be written by a Cabinet Secretary on the President's Task Force for Energy and Climate. This Secretary was puzzled about why the Secretary of Energy projected that United States CO_2 annual emissions would continue to grow rapidly in the future, even though the President said that the United States would pursue aggressive programs to improve energy efficiency and develop renewable energies.

The article is written in an informal style, with conversations among the imagined composite Secretary, two students, and a wizened professor and researcher. I hope that you will read the article. I think that it provides insight into the climate and energy problems, and the prospects for dealing with them. Let me show just two charts from the paper.

Fig. 24. World energy consumption (top) and world CO_2 emissions (bottom) based on data from EIA (13). Pie charts are the division of energy use and CO_2 emissions among countries in 2002. Line graphs show the histories since 1980 including the annual growth rates.

The first one is the division of world energy use on the top and CO_2 emissions on the bottom. The U.S. is responsible for the largest single chunk of CO_2 emissions, about ¼ of the world total. Thus if the U.S. could flatten out and begin to reduce its emissions, that would be important in itself. Moreover, as a world technology leader, if the U.S. finds ways to be more fuel efficient, it is likely to spill over to other countries, who will be just as eager to save fuels and remain competitive.

The graph on the right shows that the growth of U.S. emissions in recent decades has been about 1% per year, even through very prosperous times such as the 1990s. So, if there were an honest aggressive effort to improve efficiencies would it be possible to find savings of a magnitude to reduce the growth rate from 1% to 0%? And remember part of the energy might be supplied by renewable energy sources, so to reduce the growth rate of CO_2 emissions to 0%, the requirement for the alternative scenario, does not require reducing energy growth rate to 0%.

What the A-Team learned, and is quantified in the article, is that the main obstacle to flattening out total CO_2 emissions is rapidly growing CO_2 emissions from vehicles. So the A-Team developed an Auto CO_2 Tool that is available over the web. It allows users to see how different assumptions about automobile technology will change emissions.

Fig. 25. CO_2 emissions in the United States from automobiles and light trucks. Vehicle sales are assumed to increase throughout the period by 140,000 per year, the proportion of new light trucks and automobiles is the same as in 2003, vehicle survival rates are the same as for 1990 vehicles. The "No Actions" or base case has MPG for new vehicles the same as in 2003. "Jorge's choice" phases in by 2015 new vehicle improvements of 4.8 MPG for light trucks and 2.8 MPG for automobiles. "Moderate action" has new vehicles achieving the NRC (14) 'Path 1.5' emission reductions by 2015 and 'Path 2.5' by 2030. "Strong action", in addition, introduces advanced hybrid-electric vehicles beginning in 2015 achieving 20% of the fleet by 2030 and 40% by 2050, and hydrogen-powered vehicles beginning in 2030 and achieving 30% of the fleet by 2050.

The next figure is an example. The top curve is the actual and projected CO_2 emissions from the U.S. automobile and light truck fleet with no changes in current efficiencies. Jorge, one of the students studied various reports of the auto industry, the National Resources Council, and the California Air Resources Board, and he selected a few available proven technology options that were estimated to improve the efficiency at an added vehicle cost that could be covered via fuel savings if the cost of gasoline were $2 per gallon. The efficiency improvements were 2.8 MPG for automobiles and 4.8 MPG for light trucks, which consists of SUVs, pick-ups and vans. These modest efficiency improvements are assumed to be fully implemented by 2015. The impact of the improvements then must phase in as old cars die and are replaced. But already by 2030 the savings from these modest 2.8 and 4.8 mpg improvements is 3,200,000 barrels of oil per day. The integrated savings by 2050 is equal to 4 times all of the oil that is estimated by the U.S. Geological Survey to exist under the Arctic National Wildlife Reserve.

This 'moderate action' case, which saves the equivalent of more than 7 ANWRs, has efficiency improvements that are still conservative compared with what the National Research Council says could be achieved with a serious effort. Indeed, just a couple of weeks ago Ford Motor leapfrogged the NRC, saying they planned to reduce CO_2 emissions 80% by 2030.

Of course if someone promises something in 2030, we may take it with a dose of salt, because that person, if not dead, will be long-retired in 2030. Are they simply trying to avoid doing anything serious now? Similarly, a national strategy that does little for near-term efficiency under the assumption that 'hydrogen' will be a savior is deceptive. Hydrogen requires energy for its production, so efficiency will continue to be of equal value in the hydrogen era, if and when that arrives.

Note that the very modest 'Jorge' efficiency improvements, at an oil price of $40/barrel, would save the U.S. almost $50 billion per year. The moderate action case saves about $80 billion per year. If the oil cost is $50/barrel, the savings is $100 billion per year. Such reduced oil requirements have obvious relevance to national security, as well as relevance to our economic well-being.

The 'Parable of the Secretary' ends with the Secretary telling the students and professor that their report was appreciated by the Task Force on Energy. Statements in the report will be adopted in official documents, but no action taken. The students, who had worked so hard, are crushed and wonder if they were naïve. But the parable holds out hope that the final chapter may not be written in stone.

Summary

I will summarize now the status of understanding of global climate change, from my perspective. It is based on my knowledge and insights about the atmosphere and climate developed over the past few decades, for whatever that is worth, and I make no special claims about that. However, I can also say with some confidence that it is broadly consistent with the views of most of the scientific community with expertise in this topic, as represented, for example, by the Intergovernmental Panel on Climate Change.

It don't see how to speak in a forthright manner about this topic without appearing to be critical, which invites counter criticisms of ones own frailties. I remember back in my youth, when we finally got a black and white television, there was a 'western' in which one of the men driving a wagon waxed philosophical, repeating a refrain of one of his parents "There's so much bad in the best of us, and so much good in the worst of us, that it ill-behooves any of us, to (be critical of) the rest of us." The last line a paraphrase; my memory from that long ago isn't perfect. Nevertheless, despite that admonition, I will be frank on this topic.

1. Dangerous Anthropogenic Interference

The "business-as-usual" scenario for energy use and CO_2 emissions leads to global warming of at least 2-3°C, based either on any climate sensitivity consistent with empirical data from the Earth's history or based on the most advanced global climate models. Such a degree of warming will make the Earth at least as warm as in the middle Pliocene, a time when the Earth was a different world, with sea level about 25 meters higher than today. I'm not implying that sea level would rise 25 meters this century, but it would rise a good deal with a lot more in the pipeline.

Is it all right for us to set the world on a course aimed at such a state without stopping to ask whether this might constitute dangerous anthropogenic interference with nature? Just over a year ago I gave a presentation to NASA Administrator Sean O'Keefe, which was a summary of a presentation "Can we defuse the global warming time bomb" that I had given to the Council on Environmental Quality" in June of 2003. When I put up the viewgraph with meltwater rushing into the moulan on Greenland, with title 'what determines dangerous anthropogenic interference', and suggested that we may be closer to dangerous interference than is generally realized, the Administrator interrupted me. He told me that I should not talk about dangerous anthropogenic interference, because we do not know enough or have enough evidence for what would constitute dangerous anthropogenic interference.

It was several months later before the analogy with the NASA space shuttle tragedies dawned on me. There were engineers who suspected the 'O-ring' dangers with a cold shuttle launch, and there were engineers who were concerned about potential damage from foam insulation bouncing off the shuttle. But they were strongly discouraged from passing that information to the highest levels, where it might have been possible to prevent the tragedies.

The highest level requiring information on climate change, it seems to me, is the public. They are the ones affected by climate change, and they must decide how seriously we take the issue. So my primary recourse is to write articles that communicate the matter as clearly as I can. The present example is the article "On the Road to Climate Stability", also called "The Parable of the Secretary", which we will submit for publication soon.

2. Communication of Scientific Information

I also want to comment on communication of scientific information. On the topic of global climate change, communication with the public has become seriously hampered during the past few years for employees of government agencies such as NASA, NOAA and EPA. Although one can try to ignore attempts to influence communication, overall the effects have been substantial. Most scientific information to the public flows through public information channels. I show here a specific recent example (Figure 26).

Fig. 26. New review process for Earth Science press releases.

Yesterday I asked people in the NASA Goddard Earth Science News Team if they were willing to corroborate this. I was told that I could "not expect to get cooperation" on this, that "we have already been spoken to about this" and "we could be fired". Instructions, oral instructions, regarding required White House approval of science results on climate change were delivered from the NASA Associate Administrator for Public Affairs to the Goddard Public Information Officer for Earth Sciences and on down to the lower levels of public information officers. I should note that the Associate Administrator has denied that any such White House approval process has occurred. I also note that the Science Advisor to the President, Dr. Marburger, an outstanding scientist and a superb administrator of unquestionable integrity, has said, in the New York Times last week, that "This administration clearly has an attitude about climate change and climate science, and it's much more cautious than the previous administration. This administration also tries to be consistent in its messages. It's an inevitable consequence that you're going to get this kind of tuning up of language."

I believe that this is a case where reasonable individuals can have differing opinions on a basic matter. I respectfully assert that Dr. Marburger has understated what is a serious misrepresentation of scientific results. In my more than three decades in the government, I have never seen anything approaching the degree to which information flow from scientists to the public has been screened and controlled as it is now. I am referring specifically to research on climate change that yields results of possible public interest that would likely be interpreted as being relevant to policy considerations on climate change. The process that occurs is as follows.

First, there is a selection of what results will be reported publicly. Results that yield evidence of natural climate variations, or which cast doubt on interpretations of anthropogenic climate effects, receive favorable treatment and are promptly disseminated. Results that would raise concerns about climate change are slowed and in some cases dismissed as not of sufficient interest for public dissemination.

Second, there is commonly a massaging of the text of the scientific messages that are presented. Wording is altered to make the message about climate change to appear to be less serious, or, among the various results in a paper, the ones highlighted are those that do not raise concern about climate change.

This process is in direct opposition to the most fundamental precepts of science. I refer you again to the quotation of Richard Feynman: "The only way to have real success in science … is to describe the evidence very carefully without regard to the way you feel it should be. If you have a theory, you must try to explain what's good about it and what's bad about it equally. In science you learn a sort of standard integrity and honesty."

3. Relevance to the environment

The question is: does this concept of how science works have any relevance to the environment or to policies relating to the environment? I think that it does. If the evidence from science is distorted, if there is a selection from the scientific results of those bits that support a predetermined course of action, this is a dangerous anthropogenic interference with and a misuse of the scientific process. How can the phrase "sound science" be applied to results emanating from a procedure that flies in the face of the fundamental basis of science?

I know that such interference with and misuse of the scientific process is occurring now to a degree unprecedented in my scientific lifetime. I speak from a position of having tried hard to work with and advise the current administration on matters relating to climate change. I find a willingness to listen only to those portions of scientific results that fit predetermined inflexible positions. This, I believe, is a recipe for environmental disasters.

I refer most specifically to evidence that relates to the desirability and feasibility of measures to reduce emissions of carbon dioxide. Evidence that this is necessary for achieving climate stability and avoiding dangerous anthropogenic interference with climate has become overwhelming, but it continues to be dismissed or downgraded via the distortions of the scientific process discussed above.

I want to emphasize that, in my opinion, the measures needed to achieve a slowdown in our emissions of carbon dioxide are not only achievable, but they would have benefits for our economic well being, energy security, and thus national security. A statement such as this last sentence involves personal assessments, and there is room for disagreement on such basic matters. I hope that you will read the draft article, "On the Road to Climate Stability", and make your own assessments. I would be pleased to receive your criticisms and suggestions for that article, which has not yet been submitted for publication.

4. Disclosure

Given the relevance of climate, energy and the environment to national politics and the upcoming election, I want to disclose potentially relevant personal information. I consider myself to be moderately conservative, middle-of-the-road. I am registered to vote in Pennsylvania as an independent. My favorite for the President would be John McCain, but he is not on the ballot.

Because of all the hoopla around global warming in the 1980s, I had the privilege of meeting lots of people in Washington. To me the most impressive one, who would have made a great President in my opinion, was a Republican Senator from Pennsylvania, John Heinz (conceivably I am biased because he told me that he had once protected me from John Sununu). John Heinz was someone who gave appropriate weight to both economic growth and the environment, the latter being a passion of his.

Several years ago I received the Heinz Environment Award. I don't know who nominated me for that award or how the selection works. I am confident that it has no impact on my evaluation of the climate problem or on my political leanings.

In the upcoming election I will vote for John Kerry. I have reservations. I don't like his appeal to Nevada voters by promising there will be no nuclear waste disposal there. Nuclear waste disposal is an important technical problem that is not insurmountable, but the more it is politicized the harder it gets. However, overall, in my opinion, John Kerry has a far better grasp than President Bush on the important issues that we face.

As for the area in which I have expertise, climate change and it relation to energy use, my impression is that John Kerry intends to call in industry leaders, tell them that climate change is something that they must deal with now, and offer to work with them. He is certainly not in denial of the existence of the climate change problem.

5. Professor Van Allen.

This month, when Iowa celebrated the 90th birthday of Prof. Van Allen, it revealed the large number of people whose lives were touched by Prof. Van Allen, and not only with regard to teaching them science. I noted to my wife Anniek last week-end that if it hadn't been for a letter from Van, I would not have got an NSF Fellowship to study in Leiden, where I met her. She responded very unromantically, "well you would have met someone else." I was looking through old papers, seeing if I had correspondence with Prof. Van Allen from the 1960s. I vaguely remembered a few things, such as him chastising me for not sending in a photo for the Department's collections of graduates, maybe some of you have been chastised for that. We didn't find correspondence, although Anniek had saved the photo, probably because that was from the brief period when I had lots of hair.

But what I did find last week-end was an exchange of letters with Prof. Van Allen in the 1980s. I had written to him in part because I heard something at NASA Headquarters that suggested his proposal for an instrument on a mission to Jupiter may not be selected because of his criticisms of the manned space flight program. In his return letter, as if to put this matter in its proper place, he referred to it only in a postscript, which read: "P.S. I do understand that my criticism of NASA's emphasis on the shuttle, on manned space flight, and on the space station has not endeared me to NASA management but I have taken the position that I am dealing with honorable individuals, who understand that there is room for differences of opinion on these basic matters. I have never detected any clear case of a reprisal but there may be such on a subtle level." End of quote and letter.

It is not only Prof. Van Allen's accomplishments in science that his students can only dream of emulating. He is, in reality, a man for all seasons.

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Figure Legends

Figure 0. Abstract.

Figure 1. (a) Parents and older sisters. (b) With four older sisters and friend.

Figure 2. The Goldilocks Planets.

Figure 3. Feynman Quotation.

Figure 4. Temperature anomalies in 2004, relative to 1951-1980 mean (reference 1).

Figure 5. Global mean temperature change, based on meteorological stations before 1900 and stations plus sea surface temperatures after 1900 (reference 1).

Figure 6. Climate forcing agents in the Industrial Era (reference 2). A climate forcing is a mechanism that alters the global energy balance. A forcing can be natural – fluctuations in the sun's brightness, for example – or human made, such as aerosols and greenhouse gases. Human-made climate forcings now dominate natural forcings.

Figure 7. (a) Sophie explains greenhouse warming to Conner, (b) Connor, though only 5 months old, gets it: it's 2 Watts of forcing.

Figure 8. Vostok (Russian base in central Antarctica) temperature for past 400,000 years (reference 3).

Figure 9. Vostok carbon dioxide, methane, and temperature record for the past 400,000 years (reference 3).

Figure 10. Ice age climate forcings imply a climate forcing of ¾°C per W/m^2 (reference 4).

Figure 11. Estimated climate forcings during the past 150 years (reference 5).

Figure 12. Observed and simulated global surface temperature change for forcings of Figure 11. The five model runs differ in initial ocean and atmosphere conditions, and thus follow their own chaotic paths (reference 5).

Figure 13. Global climate simulations driven by forcings of Figure 11 (reference 5).

Figure 14. Ocean heat content change between 1993 and 2003 in top 750 meters of the world ocean. Observations from reference 11. Climate model the same as in previous two figures, driven by climate forcings in Figure 11.

Figure 15. CO_2, CH_4 and temperature records inferred from Antarctic ice core and recent in situ measurements (reference 6). Time scale after 1850 is expanded to allow changes of the past century to be seen. The indicated global temperature anomaly, relative to the 1880-1899 mean, is estimated to be half of the Antarctic temperature anomaly.

Figure 16. Moulin photo: What determines "dangerous anthropogenic interference"? (Roger Braithwaite photo, from reference 2).

Figure 17. The area with summer snowmelt on Greenland in 1992 and 2002 (credit).

Figure 18. Ice discharge from Greenland. Flow velocity from Jakobshavn ice stream increased ~40 in past three years (Waleed Abdalati, AGU presntation; photo courtesy of Konrad Steffen).

Figure 19. Precipitation changes with increasing CO_2 and "all forcings" in 2000 (reference 7).

Figure 20. The Faustian bargain. Humans have enjoyed the fruits of the industrial revolution and avoided a large cost in climate change, as aerosol cooling has mitigated greenhouse warming. Payment comes due when humanity realizes that it cannot tolerate the further exponential growth of air pollution that would be needed for continued mitigation of global warming.

Figure 21. Global surface temperature simulations extended through 21st century (reference 5).

Figure 22. (A) Annual growth of atmospheric CO_2 based on measurements through 2003 and on scenarios of IPCC (reference 8) and Hansen and Sato (reference 9). Fossil fuel emissions are continuing to grow as shown by the top curve in (B). The average fraction of emissions that remains airborne (C) continues to be about 60%, implying that the underlying CO_2 growth rate is now 1.9 ppm/year, closer to the IPCC (2001; reference 8) scenarios than to the "Alternative Scenario" (reference 10).

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