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# LETTERS

## The Future of Fusion

Jan Beyea's contribution to the fusion discussion (January 1990) seems to me to present a plank in the environmentalist platform rather than to give a penetrating analysis of actual public attitudes. While environmentalists do have strong allies in the media, in academia, and in the leadership of influential lay organizations, the public has been known to go in a different direction when it at last senses that its own interests are not being served by the orthodoxy.

Many years ago the head of the local labor union said to me "Let's face it, there's no industrial hazard that can't be eliminated by a dollar an hour wage increase!". Nowadays this observation would be considered too crass to be openly expressed. Nevertheless, the stacks of unsold radon detector kits gathering dust in hardware stores suggest the continued willingness of members of the public to discount even widely publicized hypothetical hazards. We are constantly warned of the need to protect "Spaceship Earth." But the public may come to realize that, on a perilous journey, the agonizing decisions must be based on more objective analyses of the comparative risks of alternative courses of action and more attention to technological constraints than has been customary in the environmental movement.

With respect to fusion power, the real issue seems to me to be whether or not fusion power plants can be as safe and economical as the advanced fission plants that are being designed by U.S. vendors for off-shore use. I don't know whether or not Beyea and friends would consider these plants to be "melt-down-free." But, having the ability to perform my own risk assessments, I would rather my grandchildren live near an advanced LWR than in one of the sealed up homes prescribed by proponents of energy conservation.

It will admittedly be more difficult for fusion power plants to compete with advanced LWR's than with a duplicate interstate highway system covered with expensive PV devices, installed and maintained by an army of workers whose enthusiasm for solar energy is not guaranteed to lead to unprecedented restraint at the bargaining table. If fusion scientists and engineers are willing to accept the greater challenge, they deserve our continuing support. On the other hand, I question the wisdom of devoting major societal resources to the pursuit of standards of safety that are far more rigorous than those utilized by members of the public in making their own "real life" decisions.

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The January issue carried four articles that dealt with the "Future of Fusion." These articles, and others on this subject that I have seen elsewhere, make no mention of what I feel is the reality that will prevent nuclear fusion from having a major impact on our national energy scene for several decades. By "fusion" I mean fusion that might be achieved by the traditional mechanisms that are being explored in mega-machines that heat plasmas or that implode pellets. The "reality" to which I refer is the complexity of commercial power systems that might evolve from those experiments.

Most of the proposals that I have seen for commercial fusion power would use the fusion process as a source of heat which would convert water into steam which would drive turbines which would then drive electric generators. The primary commercial product of the fusion systems would be power for the nation's electrical grid.

We have had over one hundred years of experience with the production of electricity from steam plants that burn fossil fuels. The dependability and reliability of these steam plants is one of the marvels of the age in which we live. In my memory I can't recall one of these plants exploding. Their concept is simple, their design and engineering are superb, and their output has reshaped our society. Our society now requires absolute dependability of our electricity as to voltage, frequency, and capacity and outages of electrical power have a severe economic impact on all who are affected. Fortunately outages are rare. This is the game in which any new source of electric power must compete. Increasing complexity of a system is a major adverse factor in the ability of the system to compete. Nuclear fission power plants are one or two orders of magnitude more complicated than the fossil fuel plants with which they must compete. It is a credit to all involved that nuclear fission electric plants have done remarkably well in spite of their inherent complexity. But there have been disasters, and the political problems surrounding the disposal of the waste from these plants remains unsolved. It may well be that today's nuclear fission power plants are about as complex as can be managed by humans where the requirements of reliability are so stringent, and where the societal costs of even occasional catastrophic failure are so high.

It seems reasonable to predict that nuclear fusion power plants will be one or two orders of magnitude more complex even than nuclear fission plants. As a consequence, the probability seems low that they could supply reliable 60 Hz power 24 hours a day for years at a time.

I don't recommend that we stop our research on nuclear fusion. However, the combination of the inflexibility of our high performance requirements for electric power systems and the almost certain complexity of possible nuclear fusion power plants, leads me to make an observation and a prediction.

Observation: It would be unwise for energy planners to count on any schedule of proposed or predicted availability of commercial quantities of electric power that is generated by nuclear fusion.

Prediction: Children born today will not live to see ten percent of our national energy consumption being supplied by terrestrial nuclear fusion power plants.

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## Global Warming Causes: Population or Lifestyle?

Recently two quite different prestigious sources have commented on the causes of global warming, but with quite different root causes:

1. The University of California held a workshop on global climate change during the summer of 1989. The workshop combined the strengths of the nine UC campuses and the three DOE labs under UC management (Lawrence-Berkeley, Lawrence-Livermore, Los Alamos). They concluded that "Population growth is the single most important force driving global environmental changes" (from *Global Climate Change Newsletter 1*, #4, p. 9, Nov 1989).

2. The Pope also has spoken out on the global ecological crisis, but on the other hand the Pope stated that "The seriousness of the

ecological crisis lays bare the depth of man's moral crisis." He appealed to modern society to take a "serious look at its life style" in a world given to "instant gratification and consumerism." He called for "simplicity, moderation, discipline as well as a spirit of sacrifice" as ingredients of a healthier global society (*Los Angeles Times*, 6 Dec 1989, p. A6).

The juxtaposition of these two studies is most interesting. Is the cause of the global greenhouse population growth or lifestyle? Why does one study name population growth (and not lifestyle) and the other study name lifestyle (and not population)? Is one correct and the other wrong, are they both correct, are they both wrong, or are they both partly correct and partly wrong?

As an old adage has it, "we stand where we sit." The University and DOE scientists feel that conservation by denial is impossible politically, so they refrain from attacking the superfluous use of energy. They conclude that we should (1) use energy more efficiently, and (2) use fuels that produce less $CO_2$. On the other hand, the Pope attacks the superfluous use of carbon fuels, but does not wish to support birth control. Thus he too is silent on one part of the problem, population growth.

In fact, annual global carbon dioxide production (C) can be written as

$$d(CO_2)/dt = C = PE/h + N.$$

where P is the global population of about 5 billion people, and E is annual average per capita consumption of energy. The product of P and E is presently about 100 million barrels of oil/day, or 200 quads (1 quad = $10^{15}$ Btu) of energy/year. The symbol h represents the average amount of usable energy produced per unit energy. The value of h for a particular process varies between almost zero (house fire) to almost infinity (fission, photovoltaics, fusion). Improved end-use efficiency can help a great deal; for example, new refrigerators are now using one third as much energy as before the oil embargo, increasing h by a factor of three. At present, E divided by the average value of h is about 5 giga-tonnes per year of carbon. The last term, N, is the net production of $CO_2$ by natural causes.

The logarithmic derivative of this equation gives us the fractional rate of increase of C:

$$(dC/dt)/C = (dP/dt)/P + (dE/dt)/E - (dh/dt)/h$$

For simplicity, we have ignored man's impacts on the natural production of carbon, by assuming that $dN/dt = 0$. Actually man's impacts should not be ignored since the cutting and burning of trees can be large, and increased global warming can release methane, a very effective greenhouse gas, from the tundra. The fractional increase in population, (dP/dt)/P, is the large term at about 1.8% per year. However, the large use of energy by the industrialized states is clearly part of the problem since the world is aspiring to attain our life style.

Thus, it looks like both reports are partially correct. UC/DOE favors the first term, the fractional growth of population (dP/dt)/P, as the most important term in the equation. On the other hand, the Pope considers the second term, the excess consumption of fossil fuels (dE/dt)/E, as the most important term. On the other hand, the energy conservers, the nuclear power advocates, and the photovoltaic fans all agree that the diminished use of fossil fuel through either end-use efficiency or alternate, nonfossil power sources is the most important.

I congratulate the two groups for pointing out the two leading terms as the main cause of global warming. I agree that a global population increase of 1.8% per year is large, but I also recall that our life-style got us into trouble in the first place. We are all part of the problem as well as part of the potential solution: I confess to contributing to (dP/dt)/P by having three children, and to (dE/dt)/E by visiting our son in Paris this coming summer at his new job.

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# ARTICLES

## The Case for Civil Defense in Nuclear War Education

*Robert Ehrlich and Jane Orient*

[A copy of the original lengthier version of this article, including 48 footnotes, can be obtained from the first author.]

A majority of educators teaching courses on nuclear war and peace profess to believe in the importance of presenting both sides of controversial issues. Yet the pro side of the civil defense issue is seldom presented without the ridicule often used by its detractors. In fact, many nuclear war courses do not include *any* significant amount of material about civil defense. This may be because most educators feel very strongly that nuclear war is unsurvivable, or perhaps that thoughts of nuclear war survivability are an obstacle to peace. This article argues that civil defense advocates should be allowed to make their own case, so that students can decide for themselves whether or not the idea deserves to be ridiculed.

This essay defends the proposition that civil defense measures (shelters, food and medicine stockpiles, evacuation plans, and most importantly, education about protective measures) could save many millions of lives in the event of a nuclear war. We stress the word "could" because skeptics can always come up with some condition under which any given protective measure will fail to work.

For example, consider the idea of evacuating "high risk" areas prior to an attack—a particularly controversial civil defense measure. Evacuation of "high risk" areas would be futile in the event of an attack without warning, even though most observers believe that such a "bolt-out-of-the-blue" attack would be highly unlikely. Likewise, skeptics can point to the extreme difficulty in evacuating particular cities such as New York even given several days notice, but New York is far from typical in terms of its ease of evacuation. Skeptics also note that an attacker can simply retarget fleeing populations, but this would only be an effective tactic if the attack occurred relatively soon after the start of the evacuation, and before the population dispersed. Finally, skeptics note that even if evacuation "succeeded," no place in the nation is safe given the lethal levels of fallout radiation, "nuclear winter," or other such global threats to life. A detailed rebuttal will be given later. For now we reemphasize that the issue of how well city evacuations would work is undecidable, short of an actual nuclear war. Circumstances under which it *could* save many lives include (a) most likely nuclear war initiation scenarios, (b) most cities, (c) most strategies of an attacker, and (d) most realistic estimates of seriousness of the long-term threats to life (fallout and "nuclear winter").

For most Americans, civil defense is an issue of very low saliency. If reminded in a poll that the Soviet Union spends far more on civil defense than the U.S., most Americans favor increasing U.S. expenditures. However, it is not an issue about which most citizens are particularly concerned, especially now that the perceived risk of nuclear war seems to have diminished greatly. Those few civil defense enthusiasts that do exist are regularly derided as kooks or Dr.

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Strangelove types who actually would relish the prospects of a nuclear war. Some psychiatrists believe that "denial," the unconscious suppression of unpleasant facts, is a motivation for believing that nuclear war could be survivable. We believe, however, that the reverse is more likely the case, and that the term "denial" better fits the belief in nuclear war *un*survivability. For many Americans the thought of experiencing the kind of unpleasant hand-to-mouth existence prevalent in 90 percent of the Third World today, a realistic prospect for survivors, is simply unimaginable. It is more comforting to imagine one's instantaneous annihilation in a nuclear war. In reality, of course, far more people would suffer slow, painful deaths, especially those who died from radiation sickness — deaths that could be prevented by taking precautions, some of a relatively simple nature.

For example, fallout radiation (present on dust particles) can simply be washed off food without the food being contaminated afterwards, and contaminated water can easily be decontaminated by simply filtering it through an earthen filter. Another simple protective measure unknown to many civil defense skeptics who think in terms of special purpose fallout shelters is the simple expedient of survivors staying in their own home basements for a week or two following a nuclear war. This measure wouldn't work for everyone: those without home basements, those not at home when the attack occurs, those whose homes burn down, etc. But for those living in perhaps 75 percent of the nation's land area, a ten to twenty-fold reduction in the radiation level (as a below ground basement provides) is enough to make survival possible. Of course some areas of the country would become "radioactive wastelands" in the sense that a very long time would be required before radiation levels decayed to safe levels. In those very "hot" areas, survivors would need shelters with a protection factor much higher than 10 or 20, and shelter stays longer than a week or two would be required. But such areas occupy a relatively small percentage of the nation's land area.

Civil defense critics often portray the situation otherwise by speaking of the vast land area that can be "contaminated" by a single nuclear explosion. In making this claim, they are either using the word "contaminated" to refer to any amount of radioactivity, however small (in which case everyone on earth is contaminated right now), or else they are referring to the present day peacetime radiation standards used by the government for limits on radiation exposure. These limits are 5 rems in one year for occupational exposure or 0.5 rems in one year for the general public. Such peacetime exposure limits are extremely stringent in terms of the health risks (primarily excess cancer deaths) faced by people exposed. The health risks faced by people receiving a given dose of radiation are reasonably well-known (at least for high doses), based on studies of the survivors of the Hiroshima and Nagasaki bombings. For example, the rate of increase in cancer deaths (most 20 or more years later) was found to be about 8 percent for every 100 rads a survivor received.

In discussing the dangers of fallout from nuclear weapons, people often mention the islands in the pacific that remain "uninhabitable" as a result of U.S. nuclear testing, despite a radiologic clean-up operation. In fact, the radiation on the Marshall Islands is somewhat higher than it was before the testing. But it is still not very high. The Northern Marshall Islands Radiological Survey conducted in 1978 showed that on most of the islands the annual dose due to fallout was about 0.006 rems from all exposure pathways, including food, or about 4 percent of the average annual external background dose in the U.S. On Bikini Island, one of the most heavily contaminated areas, the maximum annual dose to those eating locally grown food was less than 2 rems.

One other greatly-feared effect of radiation on humans and animals is genetic mutations. Studies on the survivors of the Hiroshima and Nagasaki bombings have, however, shown no evidence for an increase in the 10 percent spontaneous rate of genetic defects among survivors' offspring. This does not mean that no increase occurred, only that it was too small to be seen given the size of the group studied. Extrapolations from studies with mice indicate that a small increase would probably be expected, but certainly nothing like the popular misconception, shared by many nuclear war educators, of radiation producing a new breed of "monsters" among nuclear war survivors— a favorite theme of science fiction and editorial cartoons.

Radiation is only one of numerous threats to human survival in nuclear war. Other immediate or early sources of casualties would include blast, thermal radiation, and fires. Later, people might perish from starvation, disease, climate change ("nuclear winter"), or other factors. Yet none of these factors, singly or in combination, has been shown to pose such an overwhelming threat that all protective measures would necessarily be useless.

Consider, for example, the "duck-and-cover" drills of schoolchildren in the 1950's, which are still taught to all Soviet citizens today. Although widely ridiculed, such simple action could save many people outside the lethal blast area who might otherwise be severely injured from flying glass or from the intense thermal radiation which could cause severe burns or temporary blindness.

Obviously, inside the lethal blast zone, measures to protect lives would need to be much more elaborate (blast shelters), but it should be noted that the cumulative U.S. area subject to such lethal blast damage (over 5 psi) is probably less than 5 percent (and for the U.S.S.R. it is probably less than 1 percent). These figures will probably surprise most people who may have heard the widely repeated assertion that we and the Soviets have enough nuclear weapons to kill each other 10 or more times over. Other variations on this theme are that the world's arsenals equal one million Hiroshimas, or three tons of TNT per person on Earth, or our favorite: a hand grenade for every square foot of the Earth's surface.

If these latter "statistics" are true how is it possible that less than 5 percent of the U.S. (or 1 percent of the Soviet) land area would probably be subject to lethal blast damage in an all-out nuclear war? The early calculations of deaths per megaton were based on a "cookie cutter" model. Each nuclear detonation is assumed to result in lethal blast damage inside a circle of specific radius. One then imagines nonoverlapping circles to be placed over the areas of greatest population density. In this way, it was estimated that perhaps 400 one-megaton weapons could kill about 25% of the population. This 25% fatality level was considered by strategists in the 1960's to represent a level of damage that no nation would tolerate — the "assured destruction" level. "Assured destruction" does *not* mean that everyone would be killed with 400 megatons. Moreover, the present U.S. megatonnage of ten times this amount would not kill everyone either, even in the simplified "cookie cutter" model. The reason is that a point of diminishing returns is reached fairly quickly after the major population areas are targeted, and each additional megaton used would kill fewer and fewer people; the major urban areas of the nation occupy no more than 2 percent of the U.S. land area, and no more than 0.2 percent of the Soviet land area.

In fact, on a worldwide basis all the weapons in all the world's arsenals would subject less than 1 percent of Earth's land area to lethal blast pressures. Thus, the "overkill" statistic about being able to kill each other ten times over is at best a metaphorical use of numbers that has no relation to actual casualties, and at worst a deliberate attempt to mislead people into believing nuclear war survival is impossible. That statistic (as well as all the others: 3 tons of TNT per person, one million Hiroshimas, etc.) have as little bearing on the actual estimate of casualties as the observation that the explosive power in the world's nuclear arsenals is comparable to that released in one very large volcanic explosion

The fact that only a relatively small percentage of the nation's land area would be subject to lethal blast damage makes evacuations of cities prior to nuclear attack a conceivable strategy. This, of course, is not nearly as effective a strategy as having in-place blast shelters that can be occupied on short notice, but for a nation that doesn't wish to pay the expense (estimated at 60 billion dollars or $250 per blast shelter occupant) it is the next best possibility. Obviously, an evacuation of cities would pose extraordinary problems for people residing in the "host" areas. And even outside the "high risk" areas, there still would be many other hazards, especially fallout.

Often, the ability of people to survive the short-term effects of nuclear weapons is portrayed as "meaningless" in view of the long-term environmental effects. One example of such predicted effects is the depletion of the ozone layer which supposedly has been linked to various human activities. The primary human hazard of a depleted ozone layer would be an increase in skin cancers due to ultraviolet radiation. Calculations by the National Academy of Sciences estimate the rate of increase following a nuclear war to be about 10 percent for Northern Hemisphere survivors — roughly one tenth the increase in danger faced by someone who today chose to move from Minnesota to sunny Texas!

The long-term consequence of nuclear war that has received the widest publicity as being possibly serious enough to bring about mankind's demise has been "nuclear winter," originally proposed in 1983. More recent studies by Thompson and Schneider, however, using more sophisticated models than the 1983 study, show that the duration and magnitude of the maximum expected temperature declines (about 200 degree-days of cooling rather than 22,000), might justify the term "nuclear autumn" better than nuclear winter. Moreover, the magnitude of the climatic effect is highly dependent on factors under the control of the initiator of the nuclear war (the choice of weapons, their altitude of detonation, the targets, and the time of year). Any attacker seriously concerned that nuclear winter is a remote possibility need only choose his weapons and tactics accordingly to avoid "nuclear winter's retaliation." For example, calculations of the maximum temperature depression averaged over northern hemisphere mid-latitudes yield 15 °C for a war in the summer but only a few degrees for a wintertime war. The idea of a "threshold" for nuclear winter if one percent of the world's arsenal is used, or that any attacker would suffer as badly as his victim because of nuclear winter, are additional myths created by those who see in these positions further justifications for their long-held views on nuclear disarmament.

Given the present (and probable future) uncertainties in nuclear winter calculations it would be foolhardy to claim that worldwide climatic changes following a nuclear attack would certainly be negligible, only that they almost certainly would not be catastrophic. As S. L. Thompson and S. H. Schneider note: "On scientific grounds the global apocalyptic conclusions of the initial nuclear winter hypothesis can now be relegated to a vanishingly low level of probability" ("Nuclear Winter Reappraised," *Foreign Affairs*, Volume 64, 1986, pp. 981-1005). Of course, even with climatic changes of less than catastrophic dimensions, large numbers of people might suffer starvation from the disruption of domestic agriculture and food imports from other countries. But then the civil defense measure of prior food storage could partly ameliorate such suffering in the event of a nuclear war (or other natural and man-made hazards prevalent in many parts of the world.)

Disinterest in civil defense is not a global phenomenon. The Soviet Union, for example, spends over 20 times as much as the U.S. does on civil defense every year. Despite assertions about the unsurvivability of nuclear war made by Mikhail Gorbachev in his 1987 book, there is no sign of slackening in Soviet civil defense efforts. Soviet civil defense is often dismissed as a sham by many Americans and by selected Soviet officials by pointing to specific problem areas, using ridicule, or by citing the response to the Chernobyl accident and the Armenian earthquake. In fact, while considerable problems were encountered in the Chernobyl and Armenian earthquake disasters, Soviet civil defense also had some notable successes. Moreover, those who regard Soviet civil defense as a sham rarely cite specific details about the program, including the existence of more than 20,000 blast shelters to protect up to 175,000 party leaders, the blast doors in every subway system in the land (present in cities of one million or more population), the more than 100,000 full-time and 20 million part-time civil defense personnel, and the civil defense classes that are required of all Soviet citizens. Although the Soviet civil defense system would probably fall short in many respects if actually put to the test, CIA estimates of its effectiveness suggest that Soviet casualties in an all-out nuclear war that occurred following a week of heightened tension during which preparations could be made would probably be "in the low tens of millions," namely about 10 percent of the population.

At the same time that many deride civil defense as being incapable of coping with an all-out attack by the Soviet Union, there is a growing perception that better U.S.-Soviet relations make such an attack less likely, perhaps even the least likely, of potential nuclear threats. If that is the case, civil defense deserves reconsideration even by Doomsday theorists. The proliferation of nuclear weapons (and worse, long-range delivery systems) to Third World nations, or even to terrorist groups, poses a growing though clearly nonapocalyptic threat. Civil defense could also make a considerable difference in coping with the aftermath of the accidental launch of a few weapons.

This article cannot answer every one of the literally endless stream of arguments advanced to "prove" that nuclear war would be unsurvivable: firestorms, mass epidemics, societal collapse, insects inheriting the earth, just to name a few. Rather, it has addressed some of the commonly stated arguments in order to illustrate a general approach, to highlight some of the factual material that should be considered in reaching a conclusion, and to suggest specific sources of additional information.

If civil defense advocates are correct, then decisions about this issue could affect the lives of many millions of people in the event that nuclear weapons are ever used. Thus, a serious consideration of this viewpoint is worthy of inclusion in all courses related to nuclear war and peace.

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# Trees Can Sequester Carbon, Or Die And Amplify Global Warming: Possible Positive Feedback Between Rising Temperature, Stressed Forests, and $CO_2$

*Arthur H. Rosenfeld and Daniel B. Botkin*

### Global facts: good news and bad

Forest biomass plays an important role in the global carbon cycle. Forests store billions of tonnes of carbon in plants and soil. This is why there is currently so much discussion about planting trees to sequester a significant fraction of the carbon added to the atmosphere by human activity. The idea of forestation to offset carbon emissions was first proposed by Dyson and Marland (1, 2). To assess the viability of massive tree planting, we need to understand how planting trees and deforestation relate to the current global carbon release.

We will make a rough estimate of how much carbon could be sequestered by planting trees, and how much carbon could be released by deforestation or global warming. For the purpose of the discussion we make the following assumptions concerning the order of magnitude of various quantities and rates, some of which, unfortunately, are poorly known:

1. World combustion of fossil fuel produces about 5 Gt of carbon (as $CO_2$) each year:

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$$\text{Fossil Fuel Rate} = 5\ \text{Gt/year}. \qquad (1)$$

Figure 1 gives the Mauna Loa (Hawaii) data on the buildup of atmospheric $CO_2$. We will use it to give a simplified carbon accounting. We also need to know that the atmosphere contains about 700 Gt of carbon (as $CO_2$). This gives us the right-hand scale of Figure 1. We see that the average concentration of carbon in the atmosphere is now rising about 15 Gt every 5 years or 3 Gt/yr. This is 60% of the fossil fuel rate in Eq. 1. The remaining 40% is apparently removed by the oceans (Bert Bolin, University of Stockholm).

2. We know that for the last 160,000 years there has been an astounding correlation between temperature and atmospheric $CO_2$ and methane concentration (Figure 2).

3. Living biomass, mainly trees, contains about 500 billion tonnes (Gt) of carbon, comparable with the 700 Gt of carbon as $CO_2$ in the atmosphere. In the soil there are an estimated 2000-4000 Gt of carbon.

4. The carbon turnover rate from the 500 Gt of living biomass is on the order of 1%/year, i.e. each year about 5 Gt of carbon are sequestered by photosynthesis, and another 5 Gt are returned to the atmosphere by respiration of living biomass and by decaying biomass.

5. If we deforest 1% of the world's 4 billion hectares (Gha), we will promptly (within a few years) add 5 Gt of carbon to the atmosphere.

6. If we add an additional 1% to our forests, which will eventually sequester 5 Gt (but only over 100 years), we will have net sequestering for 100 years, but only at 1% of 5 Gt/year. In other words, in terms of delaying the greenhouse threat for 20 years while we develop non-fossil sources of energy, we have the problem that dead trees decay in a short time span compared to 20 years, but young trees grow in a long time span compared to 20 years. Thus, for a 20 year time-horizon, we must plan 5 ha to offset the carbon released by deforesting 1 ha. Thus, it is better to save 1 ha of forest than to plant 1 ha. This is an important consideration in dealing with nations which need incentives to slow their deforestation.

7. Returning to point 5, that 1% dead and decayed forest biomass represents 5 gt of carbon, we now cite a serious danger. If global warming takes place too fast for forests to adapt to changes in temperature and humidity, it is conceivable that an additional 1% of the forests could die per year. This would be very damaging positive feedback.

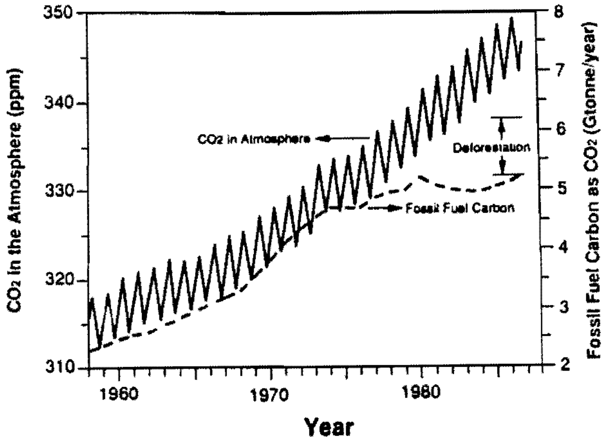

**Figure 1. Carbon Dioxide Concentration in the Atmosphere and Fossil Fuel Carbon Emissions, 1958 to 1987.** The figure shows monthly concentrations of atmospheric CO2 at the Mauna Loa Observatory, Hawaii. The yearly oscillation is explained mainly by the annual cycle of photosynthesis and respiration of plants in the northern hemisphere. The slowly increasing concentration of atmospheric CO2 at Mauna Loa since the 1950s is primarily caused by carbon emissions from fossil-fuel combustion (dashed line). The current annual rate of fossil fuel emissions is about 5 gigatonnes (Gt). Also shown is the estimated 1 Gt of carbon emissions from deforestation. Source: Charles D. Keeling, Mauna Loa, Hawaii.

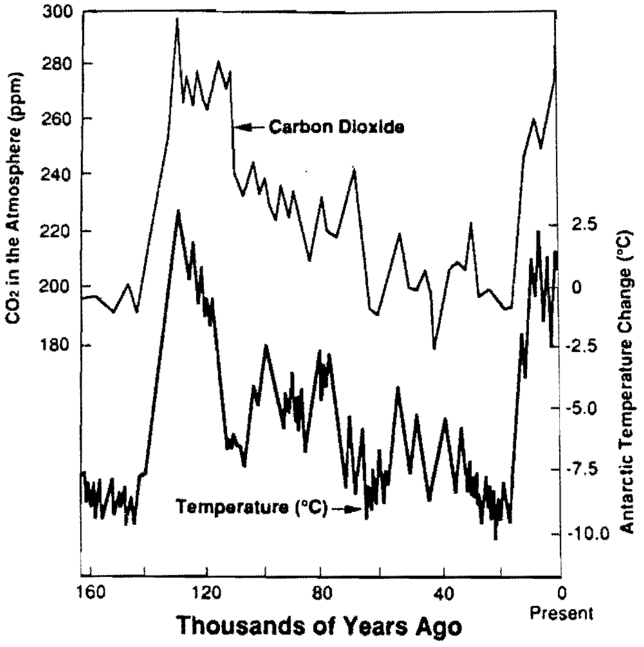

**Figure 2. Inferred Atmospheric CO2 Concentration and Temperature Change from 160,000 Years Ago to the Present.** CO2 and temperature are very closely correlated over the past 160,000 years. The long-term record, based on evidence from Antarctica, shows how atmospheric CO2 and local temperature rose nearly in step as an ice age ended about 130,000 years ago, fell almost in step at the beginning of a new glacial period, and rose again as the ice retreated about 20,000 years ago. Source: Stepen H. Schneider, *Scientific American*, September 1989—from Claude Lorius *et al*, Laboratory of Glaciology and Geophysics of the Environment near Grenoble.

How fast will forests have to migrate if fossil fuel combustion continues to rise by 1.5%/year? At this rate the carbon dioxide concentration in the atmosphere will double in about 50-70 years. Climatologists are in general agreement that a doubling of $CO_2$ and an equivalent increase in other trace gases will warm the earth's average surface temperature by 3-5 °C. About a dozen research groups around the world have developed computer models to help predict how global climate will be affected by increasing greenhouse gas emissions, and Figure 3 shows the results of one of these models (3).

If greenhouse gases double by 2050, Figure 3 shows an average warming of 3.5 °C. In the summer, for temperature latitudes, average temperatures change by about 1 °C for every 200 km north-south latitude change. If Figure 3 is correct and average temperatures rise 3.5 °C, then this would be equivalent to moving summer temperate zones 600-700 km north over 60 years. If the temperature increase is linear, the move would have to be about 10 km/year. Unfortunately, Figure 3 is more nearly quadratic—the slope starts at zero, and then increases linearly (e.g. $T = t^2$, $dT/dt = 2t$)—so that by 2050 the rate of change might be closer to 20 km/year. If the predicted global temperature increase is correct, then forests will have to migrate at a rate of 200 km per decade, by 2050. This could result in massive forest destruction. (During the last period of glacial retreat, forests had to migrate at a rate of only about 0.2 km/decade.) So a "business as usual" approach over the next 60 years is a severe threat to unmanaged forests or wilderness areas. We will discuss this quantitatively below. Massive human intervention to "help" the forests migrate north might be possible. Unfortunately, without being able to predict how rainfall patterns will change with temperature, it is doubtful that such a huge and unprecedented project would ever even get started.

8. An additional danger is that as the atmosphere heats up, biomass will decay at an accelerated rate, releasing additional carbon into the atmosphere. Aerobic decay yields carbon dioxide, and anaerobic decay yields methane, an even more serious greenhouse gas. An area

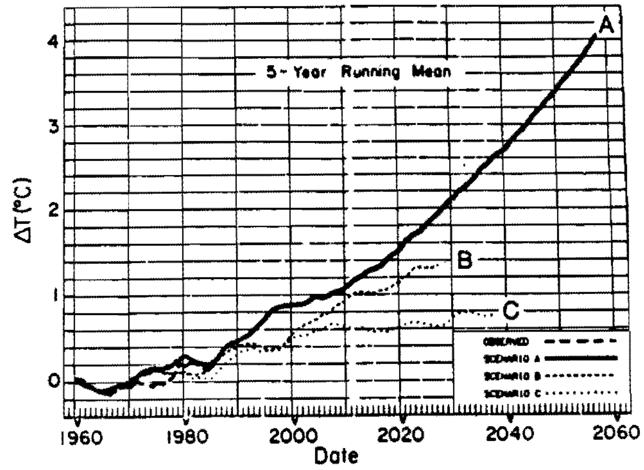

**Figure 3. Five-year Running Mean Global Surface Air Temperature Computed for Scenarios A, B, C, 1960-2060.** *Scenario A*—exponential trace gas growth, 1.5%/year; *Scenario B*—reduced linear growth of trace gases; *Scenario C*—rapid curtailment of trace gases, no increase after the year 2000.

of concern is the arctic and antarctic boreal forests and tundra where soils are believed to contain 2-5 times more carbon per unit than soils closer to the equator (4). Arctic and antarctic soils have higher concentrations of carbon because of the greater rate of vegetative growth that occurs during the warm, long days of summer relative to the slower rate of decay that occurs during the cold, short days of fall and winter. Increasing temperatures from global warming could increase the decay rate in the soil and release billions of tonnes of carbon into the atmosphere that are now stored in the soils of arctic and antarctic boreal forests and tundra.

### Photosynthesis: the good news

Next we note the oscillations in Figure 1, and remember that Hawaii is in the Northern Hemisphere, along with most of the land and vegetation. For simplicity, in the rest of this note we will assume that all the biomass in vegetation is in forests, and that all of it is in the Northern Hemisphere. The dips of the annual oscillation correspond to summer, when warmth and sunlight cause growth, increasing the rate of photosynthesis, and pulling $CO_2$ from the atmosphere faster than respiration and decomposition put it back. Then, each winter, the balance switches to excess decomposition and $CO_2$ release. We note that the summer pulldown is about 12 Gt. Only a part of this is yearly net incremental growth in the long-term storage of biomass of typical trees, the rest is leaves and twigs which fall off or are eaten, and small roots which slough off. To a first approximation we assume that,

$$\text{Growth of trees, northern hemisphere} = 5\ \text{Gt/year} \qquad (2)$$

This doesn't mean that the forests are sequestering an extra 5 Gt/year of carbon, but that carbon stored in new organic matter in forests is approximately 5 Gt/year. This increase offsets carbon release from decay. We would only get a net sequestering of carbon if we plant new trees or allow now unforested areas to become forested. Ecologists believe that the mass of carbon in vegetation is comparable with, but less than the 700 Gt of carbon in the atmosphere. Our estimate is 500 Gt, and for simplicity, we assume that all of it is forests, so that

$$\text{Forest biomass} = 500\ \text{Gt} \qquad (3)$$

By comparing Eq. (1) and Eq. (2) we see that if we wanted to plant enough forest to offset 100% of current annual fossil fuel combustion, we would have to double the forested area of the world, i.e. add 5 times the U.S. land area.

### Deforestation: the bad news

We return to point 6. Remember that 4 Gha of forest contain 500 Gt of carbon, so each hectare contains 125 tons of carbon. Suppose that we kill or clear one hectare. Then the trees will burn or decay within a few years. This is a short time compared to the time necessary for the world to switch to renewable sources of energy, and hence to the time scale of the $CO_2$ threat. For bookkeeping purposes, let's call this decay time one year. Then we see the bad news:

$$1\ \text{dead ha/year} = 125\ \text{tonnes of carbon released/year} \qquad (4)$$

Since trees take 100 years to sequester this 125 tonne/ha

$$1\ \text{newly planted ha/year} = 1.25\ \text{t carbon bound/year} \qquad (5)$$

In summer, it takes 100 years of growth to offset the damage of clearing the same area of forest.

Worse than that, suppose we let the temperature rise too fast, so that forests cannot migrate fast enough to keep up with the changing climate (or cannot adapt). Then maybe 1% of the forest would start dying each year. But 1%/year of 500 Gt of biomass corresponds to 5 Gt/year, which in turn corresponds to our fossil fuel rate in Eq. 1. If this were to happen we would double the rate of $CO_2$ release, and introduce a damaging and potentially irreversible positive feedback. We are playing with fire.

Fortunately, current estimates of human-induced deforestation is only 0.2%/year, which corresponds to 20% of the current fossil fuel rate.

### Tree planting or tree farming to sequester carbon

We can now see that it's impractical to plant trees fast enough to offset deforestation—we'd have to plant 800 Mha (1/5 of the world's forests) one time to offset killing 8 M ha/year. So let's assume that the developed world can induce the developing world to slow deforestation. Then we have a chance, and tree planting can become a useful tool.

In the industrialized countries, before the first oil crisis, energy use grew at the same rate as the Gross World Product, about 3.5%/year. After the first oil crisis, from 1973 to 1986, the industrialized countries held their energy use constant while their economies grew 2.5%/year. For a 13-year period the industrialized world proved that it could keep energy use constant *and* maintain economic growth. With the proper political leadership, we could reduce energy intensity in industrial countries by 50%, using existing technology, and still maintain the same quality of life—i.e. comfortable, well-lighted buildings, comfortable and safe automobiles, etc. If we reduce energy intensity by 50% over the next 20 years this is equivalent to a 2.5%/year improvement in energy efficiency. If economic growth continues at 3.5%/year however, a 2.5%/year improvement in efficiency translates into a 1%/year *increase* in energy use. Suppose this increase came from fossil fuel. This means just to keep world carbon emissions constant, we would have to plant enough trees to offset 1% of the 5 Gt/year fossil fuel rate.

According to Eq. 2, growing trees sequester 5 Gt/year, so we only have to add 1% annually to world forests. This would require planting 40 Mha/year of forests. This doesn't solve the problem, but it gives us an estimate of a reasonable use of trees to help keep carbon emissions constant to reduce the impact of global warming.

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# Symposium: The Forum Energy Study

The following three papers are shortened versions of background papers which will appear as part of the report of the Forum Study Group on Energy. They address important energy-related topics which have not lately been the subject of widespread public discussion. By publishing them, Physics and Society hopes to stimulate debate on these important issues. The study is chaired by Ruth H. Howes, Department of Physics, Ball State University, Muncie, IN 47306, and Anthony Fainberg, 643 G Street, NE, Washington, DC 20002.

## Energy and Transportation: Our Achilles' Heel?

*Alan Chachich*

### Introduction

A balanced analysis of energy issues must consider energy end-use as well as power generation. Transportation is a critical end-user. It claims 28 percent of the energy consumed in the United States and this fraction is increasing. The nature of this energy use is also significant as it accounts for almost two-thirds of our petroleum consumption. In fact, 97% of our transportation depends on oil. That brings us to our fundamental energy problem: a nearly total dependence on petroleum. The vulnerability of our commerce implies a direct security issue on top of the financial and environmental costs.

There are two solutions to this problem: drive more efficiently, and drive less.

I say "drive" because as the Table shows, 85% of our transportation energy is consumed on the highway. Obviously improvements to auto and truck efficiency are crucial.

**TABLE: Transportation Energy Consumption by Mode**

| Mode | Quads | % |
|---|---|---|
| Total domestic transportation | 18.61 | 100.0 |
| Highway sub-total | 15.90 | 85.4 |
| auto | 8.92 | 47.9 |
| truck | 6.83 | 36.7 |
| bus | 0.15 | 0.8 |
| Air sub-total | 1.65 | 8.9 |
| commercial | 1.50 | 8.1 |
| general | 0.15 | 0.8 |
| Pipeline | 0.50 | 2.7 |
| Rail sub-total | 0.40 | 2.1 |
| passenger | 0.01 | <.1 |
| freight | 0.39 | 2.1 |
| Water | 0.14 | 0.8 |
| Mass transit | <.02 | <.1 |

*Compiled from the "National Transportation Statistics Annual Report, 1988," DOT-TSC-RSPA-88-2.*

### Driving more efficiently

Transportation efficiency increased substantially in the last decade. Automobile fuel efficiency almost doubled from 1975 to 1986 (16 to 28 mpg). Light truck efficiency improved similarly (14 to 22 mpg). Unfortunately, this saving was offset by a 31 percent increase in highway travel. The technology for further great improvements exists or is on the horizon. It can basically be considered in two groups: advances in efficiency that will help conserve our petroleum supplies, and advances that make alternative fuels possible. Many developments of course will do both.

Of all the improvements that will reduce, but not eliminate, our consumption of petroleum, those to internal combustion engines are most critical. The primary focus here falls on leaner-burning combustion, higher compression, lower inertia for moving engine parts, shifting rejected heat from the cooling system to the exhaust stream, and recovering more energy from the exhaust. Stratified combustion is a lean burn technique that attempts to combine the higher efficiency of diesels with the greater responsiveness of gasoline engines. Advanced knock suppression techniques will determine the success of these strategies to improve combustion.

Advanced cooling techniques such as evaporative cooling and oil cooling will improve efficiency by: eliminating pumps and fans and so reducing parasitic losses, lowering engine friction via higher temperatures, improving aerodynamics (use of heat exchanger or smaller radiator), reducing warm-up time (less coolant), and lowering weight. Low heat rejection (LHR) or adiabatic engine technology may increase efficiency by 10-20%. The ongoing evolution of the LHRE has recently been discussed (1). The higher temperature operation necessary to shift heat to the exhaust will require materials to withstand the more severe environment and significant advances in high temperature lubrication. Multiple level systems employing liquid and solid lubricants together are likely. Gas lubrication is a much more distant possibility. Many schemes exist for recovering exhaust energy electrically and mechanically. They range from simple turbocharging to complicated turbocompounding systems that return energy directly to the driveshaft.

Future transmissions will keep engines operating closer to their most efficient load ranges through the use of more gears, continuously variable belts (CVT), and electronic controls. The greater stresses in the transmissions of the heavier American cars will hamper CVT application here. Electronic controls may save energy that is currently lost to inefficient shifting by drivers.

Electronic controls can save energy in many areas. The most obvious one is electronic engine control (EEC). Advanced sensors will supply instantaneous data in place of the cycle averaged data from present sensors. The myriad of electronic subsystems will eventually be integrated into cohesive fail-safe or fail-soft systems. Electronics outside the engine will also enhance efficiency. Two examples are electronic braking and sound cancellation systems. The latter could make mufflers obsolete, eliminating their load on the engine. Higher costs will be the greatest drawback of the advanced controls and sensors.

Advanced materials will reduce fuel consumption through lower weight, lower inertia parts, reduced friction, advanced sensors and increased adiabaticy. Weight reduction will make the first and likely the greatest contribution. Note that new materials may offset their higher cost through lower manufacturing and assembly costs.

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Improvements in rolling resistance and aerodynamics have been significant this past decade and will be in the next. The efficiency gains from both, particularly aerodynamics, will diminish as practical limits are reached. Engine improvements will overtake them in significance by the end of the next decade.

Work in alternate fuels falls into both groups. Developments to apply low-grade oils, natural gas and butane will help conserve petroleum supplies. Alcohols, coal, vegetable oils and hydrogen provide options which may replace petroleum. Methanol, which is actually petroleum-related, may be practical before the others. Incompatibility with the existing fuel distribution systems may be the greatest barrier to the use of alternative fuels.

Gas turbines suffer lower fuel economy and higher cost so most development will be for aviation. Road application is further hampered by the additional efficiency penalty from converting exhaust stream energy to shaft power. They are lighter, quieter, produce lower emissions and have a substantial capacity for alternative fuels and so may eventually find a place on the road.

A stirling engine vehicle is getting 10% better fuel efficiency than the internal combustion engine version. Stirling engines are also quiet and can have multifuel capability. Mass producibility and reliability remain to be demonstrated. Its much lower emissions may become the greatest incentive for further development.

Dramatic developments in the past decade showed that fuel cells can provide the most efficient power plants for transportation, (60-80% efficient). Other advantages include quiet operation, negligible pollution and alternative fuel capability. This technology also falls into both groups. Petroleum-based fuels are the easiest to apply to current fuel cells, yet in the long term they have great promise for alternative fuels. Methanol would be the most likely fuel for a transportation power plant. Poor response time is currently the greatest obstacle. Fuel cells are a high risk but high pay-off technology that can address our fundamental petroleum dependence in the longer term.

Other alternatives include electric/hybrid and solar vehicles. Mechanical and electric power storage systems under development will be crucial to many of the alternate power plants, such as electric motors and fuel cells. Recent developments in photovoltaics make it hard to judge the potential for solar vehicles, especially for the near term. Solar powered vehicles certainly would be more desirable in terms of petroleum dependency and pollution. Efforts are underway to produce electric and solar commuter vehicles. The current market may be a greater obstacle than the technical problems of cell efficiency and light-weight storage.

### Driving less

Technology can alter our transportation requirements as well as consumption. Trips can be made more effective, shorter or unnecessary. For starters, operational factors can be studied and improved at all levels. Fuel can be saved by improving individual vehicle operating practices, traffic management, and infrastructure design. An example of each would be cab heaters to reduce the idling of trucks, retiming traffic lights, and airports designed for maximum fuel efficiency.

Our transportation requirement can be analyzed as a whole, and our use of the various modes to meet it can be optimized. This would be a departure from the past as the impact of improvements in one mode on the other modes would be considered, as well as energy security, total cost, environmental impact, and safety. For example, does it make more sense to build more airports in the Northeast, or to slow air traffic growth with a magnetic light rail system or expanded highways?

We can also replace or eliminate transportation requirements directly, for example by videoconferencing, telephone banking and other telecommunication advances. Any energy use extracts a financial and environmental cost so conservation is the most beneficial solution.

### The other part

Technology is but a team member in the solution to our energy problems. Public understanding and policy are others. Policies for *both* setting research priorities and applying technologies are crucial.

Automobiles that achieve 60 to 100 mpg exist but await more favorable markets. The time constant of petroleum price swings is too short for the free-market interaction between consumers and industry to thwart a crisis. Consumers also discount the value of future energy savings heavily (20-30%) weakening the incentive for industry to concentrate on energy efficiency. In fact, as vehicle fuel economy increases, its significance to the consumer diminishes. That is because fuel costs become a smaller fraction of the total operating cost. At current gasoline prices a 10 mpg improvement to a 30 mpg auto saves the typical driver less than $100 a year. On the other hand, a 0.1 mpg improvement to the U.S. auto fleet would save 20,000 barrels of oil per day. That is the estimated production from the controversial Georges Bank fishing grounds off of the East Coast. Policies to resolve this conflict between the short term benefit to the individual and the long term needs of the nation present a formidable challenge which must be overcome.

The long term security of the nation is involved so the federal government has responsibility here. Policies must be evolved in cooperation with industry to be most effective. The free market alone may not be sufficient but the government is not likely to be able to operate an automobile company better than its board of directors. Both the industry and the government share responsibility for their past antagonistic relationship. Both must strive to leave that behind.

The government may also have to solve the "chicken and egg" dilemma posed by the automotive and petroleum industries. The major automakers do not want to invest in alternatively fueled vehicles without being certain that customers will have sufficient access to the alternative fuel. The petrochemical industry does not want to invest in the distribution network for an alternate fuel without being certain that there will be a market for it. The government may need to assume some of the risk. One option would be to subsidize centrally fueled vehicle fleets and phase out the subsidy as the market grows. Fuels could be subsidized instead. In either case, care must be taken to prevent loud but narrow political constituencies from squelching superior alternatives for their own gain.

Federal planning and action has been reactive. Consider that our contingency response policy is a few months supply of oil in the strategic petroleum reserve. That must change. We need preventive policies that will lower the probability of a supply disruption and mitigate its effects if one occurs. Policy questions that should get public attention include:

- What will it take to achieve petroleum-independent transportation?
- What will it take to achieve hydrocarbon independence?
- Then what should our long-term research goals and priorities be?
- How can we provide stable and consistent research funding?
- How do we reduce consumption? CAFE (Corporate Averaged Fleet Economy) standards?
- Can we improve the CAFE?
- Tax policies (gasoline, hydrocarbon, vehicle)?
- Incentives (reward or rebate for purchasing efficient vehicles, R & D support)?
- How can we improve public transportation?

Readers interested in detailed policy options are referred to the thoughtful discussions in references (2-4).

Finally, education must be mentioned. Without question a well informed electorate will lead to better decisions by our government and the individual consumer. The scientific community has needs here too. Specifically, we need to base our strategy for the future on our past successes. The problem is that there has been very little evaluation of what worked, what did not, and why during the last energy crisis. If we are fated to repeat that history it will not be for any good reason.

Much of the energy savings we realize now are due to programs initiated in the 1970s. The choices we make now will determine our vulnerability to the petroleum supply in the next decade or longer. We must revisit this question with urgency now while oil prices are low, especially as most experts predict a supply disruption within the next 10 years. Too much is at stake to allow ourselves to be lulled by low oil prices, when we know better.

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# Wind as a Utility Generation Option

*Jamie Chapman*

[An annotated list of selected references is available from the author upon request.]

### Introduction

As a bulk power generating option for utilities in the nineties and beyond, wind turbine electric power generating systems are among the most attractive of the renewable energy generation technologies. In their current form, wind-driven power stations represent not a replacement for conventional power stations but rather a complement, forming a part of the total generation mix. In principle, wind systems could replace a part of the existing conventional generation capacity. More realistically, they will preclude the need for or delay the addition of conventional capacity in order to meet the demands of load growth.

Wind-driven power systems represent a renewable technology which may be described as mid-course in its development and maturation. It is a renewable power technology which has evolved rapidly over the last decade and has accumulated significant, large-scale utility-connected experience, principally in California.

As a result of the impetus provided by the oil embargo of 1973, the 1978 National Energy Act, the later implementation of PURPA and by tax credit support through 1985, concerted development of modern wind turbine power systems began in the mid-seventies. Both public and private sector funding has been used to develop this technology.

The first large-scale, utility-connected installations appeared in California in 1981. Since then, private sector investment capital in excess of two billion dollars has resulted in the construction and commercial operation of wind-driven power stations whose capacity was rated at more than 1300 megawatts by the end of 1989. Thus in this country, by the end of 1989, grid-connected wind systems had provided capacity equivalent to a large nuclear or coal-fired power station.

The early experience revealed severe shortcomings in the designs of the first-generation wind turbine components. These deficiencies can be traced largely to a lack of knowledge about the extreme dynamic range and attack times of the wind and its gust structure. Second-generation designs, introduced in the mid-eighties, generally have proven themselves able to accommodate and harness these wind forces. These systems have generated substantial quantities of electricity. For example, during 1989, these systems delivered about 2 billion kilowatt-hours of electrical energy, enough to meet the residential needs of a city the size of Washington, DC or San Francisco.

### Utility-scale wind turbine power systems

*Wind-driven power stations.* Large-scale, utility-connected, wind-driven power stations frequently are referred to as wind farms, wind parks or Windplants, a trade-marked term used by U.S. Windpower, Inc.

These large-scale power generating systems are comprised of a large number of arrayed wind turbines. The power from each wind turbine is collected and combined with that from others by a wiring network similar to a utility distribution system. The collected power is then delivered through a substation to the utility grid for use by consumers. A small, central control facility monitors and controls the status of each wind turbine as well as the total delivered energy.

Except for the wind turbine components themselves, all components and subsystems which make up a wind farm are the same as used in conventional utility applications. This includes the pad mount transformers used to combine the power from several wind turbines and step-up the voltage for transmission to the substation. The substation itself, with its associated monitoring, control, switching and protective devices is purchased from the same vendors who supply utilities.

*Integration and compatibility.* The integration of wind-driven electrical generation systems with the balance of a utility system is straightforward and is accomplished using standard utility components and practices. Control and monitoring capabilities of modern wind power systems are analogous to those used for similar functions in conventional utility systems.

For current systems, there is a limitation on the amount of wind power capacity which can be integrated with conventional power sources. Based upon the second-generation wind technology currently in use, the ratio of wind to conventional power systems is thought to be in the range 5-15%. This limited range arises from the time variability and other technical characteristics of the power delivered by wind systems.

Third-generation wind systems, now in their earliest stages of development, will allow wind utilization to twice this range (i.e., 10-30%) while still maintaining existing utility standards of power quality and system stability. In certain applications, the third-generation wind systems, when augmented with moderate amounts of energy storage, will allow the conventional power sources to be turned off.

*Advantages and characteristics.* Compared with either fossil-fueled or nuclear power stations, wind-driven power stations have the advantages of modularity and much shorter construction times. Due to the distributed nature of the generation sources (the wind turbine components), wind-driven power stations are inherently modular. Capacity can be added incrementally, as required, with a short planning horizon.

In addition to their inherent modularity, wind-driven power stations can be installed and placed into operation very quickly. Therefore the cost of funds used during construction is correspondingly less. For non-renewable power stations, this cost of funds can be a significant component of the installed capital cost, and therefore of the cost of energy.

In their operation, wind-driven power plants utilize no fossil fuels or radioactive materials. Therefore there is no associated risk of environmental degradation or contribution to global warming. The capital and maintenance costs associated with scrubbers and other

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pollution control devices are eliminated. The costs and continuing risks associated with decommissioning nuclear power stations are eliminated.

Finally, the best of the second-generation wind systems currently in operation are economically competitive with newly-constructed nuclear and coal-fired power plants. The life-cycle cost of energy is 7-9 cents/kWH. Measured on a rated *power* capacity basis, the installed, all-in capital cost is in the range $1000-$1400 per kW. As a result of integrating research advances with the significant operating experience gained over the last decade, these cost values are expected to decrease to 4-6 cents/kWH and $600-$1000 per kW.

### How wind-driven power stations differ

Wind-driven power stations differ from conventional power stations in two principal ways, each with an associated consequence. These are (1) the distributed generation sources and the associated land use, and (2) the nature of the fuel and associated characteristics of the generated power.

*Configuration and land use.* Conventional utility power systems consist of a relatively small number of generation units each having a relatively large power capacity. Wind-driven power stations are comprised of a large number of geographically-distributed generating units (the wind turbines) each of moderate capacity. Whereas the size of a conventional generating unit is measured in units of hundreds of megawatts and may occupy only a few acres, an individual wind turbine typically is rated in units of hundreds of kilowatts. The array of wind turbines, which when interconnected, have a capacity equivalent to that of a conventional generating unit, may occupy a land area of hundreds of acres.

Although wind-driven power stations do inherently require more geographical area or acreage than conventional stations, the land on which wind power stations are situated can continue to be used for its original purpose. This is because the individual wind turbine sites, the service roads, substations and other supporting infrastructure actually occupy and disturb only a small fraction, typically about 10 percent, of the total area containing the wind power station. For example, the large wind installations in northern California are located on ranch land. The ranchers continue to graze cattle on their land. As another example, the 2000 wind turbines in service in Denmark are distributed throughout the country, the majority in small clusters associated with an industrial facility or group of residences.

*Fuel and power characteristics.* The fuel for conventional power generating units typically is either a fossil fuel (coal, oil or gas) or a material supporting nuclear fission. The availability of this fuel is not a function of the vagaries of nature but of production capability, logistics and storage capabilities.

The fuel for wind turbines comes without requiring industrial support and without cost. However the availability of wind, while statistically predictable, is not subject to our control. It is variable in time on various time scales: short-term (minutes and hours), diurnally and seasonally.

The energy in the wind and therefore the electrical energy delivered is reasonably predictable seasonally and diurnally. It is predictable enough so that California utilities with large amounts of wind capacity routinely factor the expected wind production into their generation planning and dispatch.

Short-term time variability is not as predictable. Thus the short-term power output from a single turbine mirrors the fluctuations of the wind. There is however some smoothing owing to inertial effects of the turbine rotor. Power electronics and adaptive control systems now being investigated for third-generation wind turbines will further smooth wind-induced fluctuations in the output electrical power.

Surprisingly, the short-term variability of the output power from an array is quite smooth relative to that from a single turbine. This is because the short-term wind time series at nearby wind turbine sites are relatively uncorrelated. When the outputs from a large ensemble of geographically-distributed wind turbines are combined, the resultant, summed power delivered to the grid can be quite smooth. The short-term fluctuations are significantly reduced, but still present.

The extreme short-term variability (minutes to tens of minutes) is the principal reason why the fraction of wind power systems delivering power to a total utility system is limited. In the simplest case, in order to deliver the constant level of power required by a constant load, the time-variability of the wind-derived power must be compensated for by increasing or decreasing the power from conventional generating units. Even if technically possible, frequent, short-term ramping up and down of these units increases their required maintenance and complicates the control and coordination of the entire power system.

In addition to the time-variability of the real (or useable) power delivered to the grid, there is a second characteristic of the power delivered by most of the second-generation wind turbine generators currently in use. Most of the wind turbines now in use incorporate (for very good design and economic reasons) a generator which requires some electrical support from the conventional power sources also on the utility grid. It is a sort of symbiotic relationship. The particular class of generators, called induction generators, require for their operation both an external voltage source and a source of reactive (or non-work-producing) power. The requirement for the so-called excitation voltage poses no difficulty and carries no economic penalty since the wind turbines must be connected to the grid anyway. However, to the extent that the wind turbines require reactive power, there is an economic penalty. This is because the conventional generation sources must be operated off of their most efficient operating point.

### Future trends

*Geographical usage beyond California.* The wind power stations installed in California generated about one percent of that state's total electrical energy needs during 1989. Two factors will increase the impact of wind energy generation in California. First, the performance of the existing plant will increase through continuing performance and reliability improvements. Second, the currently-installed capacity conservatively represents development of less than half of the state's wind resource potential.

In other parts of the US, studies published by the Solar Energy Research Institute (SERI) and by the Electric Power Research Institute (EPRI) indicate a much larger total potential for the generation of electricity by wind systems. Regions other than California include the Great Plains, the Atlantic seaboard, the Great Lakes coastal regions, the Appalachian mountains, the Aleutian islands and Hawaii.

*Technology trends.* The principal technology improvements will be associated with increases in wind turbine size, improved knowledge of structural materials and structural responses, the incorporation of improved control hardware and algorithms, utilization of power-conversion electronics, and the development and integration of short-term energy storage systems.

The power rating of wind turbines used thus far in the California installations, on average, have doubled from about 50 to 100 kW. For wind farm applications, economic optimization studies have indicated that the optimum size lies in the range 200 to 600 kW. This corresponds roughly to the rotor diameter range 20 to 40 meters.

Advances in airfoil performance and materials used for the wind turbine blades will allow the much wider geographic utilization of wind turbines. Changes in the electrical configuration of wind turbine generators, made possible by advances in power electronics and digital control, will further enhance the energy production performance of wind turbine power generation systems and make them even more competitive with fossil-fueled and nuclear power stations. Wind turbines will be self-controlling machines, able to adapt to changing wind and load conditions to a much greater extent than is currently implemented.

A major improvement in the wind turbine system architecture will be the incorporation of power electronics between the wind turbine generator and the load (the utility grid). As a wind system element, power electronics will bring several major benefits. It will allow the wind turbine rotor to be more efficient in converting power in the wind to delivered electrical power. It will provide a new control dimension which should permit lighter-weight structural elements, thus reducing the capital cost. Finally, power electronics will completely eliminate the requirement for reactive power from conventional sources. The incorporation of power electronics will be a major factor in allowing the increased usage of wind systems with conventional generation sources.

As discussed above, the principal characteristic which limits the use of wind systems without any support from conventional power sources is the time-variability of the real power. Research in and the development of cost-effective energy storage and conversion systems will smooth this variability.

### Public policy initiatives

The current era may be characterized as one of low energy prices coupled with uncertainty as to when (or whether) energy prices will rise. Practically all financial incentives for the further private sector advancement of renewable energy technology have been allowed to expire. These circumstances make it difficult to attract the investment of private-sector capital for further improvements and applications of the technology. Similarly, federal research budgets have been reduced drastically.

At the same time, there is increasing concern and knowledge about the effects of conventional power sources on our environment. And a case can be made that energy costs will increase significantly, whether as a result of geopolitical factors, simple depletion or environmental concerns and the attendant costs.

These factors, together with the general perception that there is no urgent need for renewable sources of energy, represent a unique window of opportunity. This is an opportunity of such importance that public policy can legitimately be employed to shape the future and assist in realizing the benefits offered by these energy generation systems.

Public policy initiatives to further the technical development, economics and application of wind-driven power systems (and all renewable power systems) include:

- tax incentives based upon the energy delivered;
- recognition in energy pricing of both the direct and the indirect costs of energy generation by the various sources;
- provisions in power purchase contracts offering some level of predictability for debt service of construction financing;
- majority utility ownership of renewable power systems;
- access to long-distance power transmission (wheeling) by independent power producers as well as utilities;
- incentives for the export of renewable power equipment and services.

Such policy initiatives would attract private sector capital to further the needed technical development and facilitate additional renewable energy generation facilities. This would mitigate further environmental damage, and permit US manufacturers to establish and maintain a pre-eminent export position in this capital-intensive, environmentally-important power generation technology.

# Energy Storage

*John G. Ingersoll*

### The importance of energy storage

Energy is useful only if it is available when needed and then if it is in a usable form. Keeping energy available until it is needed and in a usable form constitutes storage. Some forms of energy by virtue of their physical nature lend themselves more readily to storage than others. Two extreme examples are oil and electricity. The former can be stored in a simple and inexpensive manner in a tank or container after it is extracted from the ground. The latter requires rather sophisticated and invariably expensive means of storage such as electrochemical batteries. The problem arising from the difficulty of storage for some forms of energy may be further compounded by variability in demand and supply.

### Improving efficiency

Energy storage in general results in an efficient utilization of energy resources. Moreover, energy storage almost guarantees that certain desirable but presently uneconomic energy sources and end uses become more competitive. Three examples illustrate these points: utility load leveling, renewable energy resource use and alternative transportation means.

One of the major problems facing the electric utility industry is matching supply with demand. Traditionally, utilities have set up a three-tiered generation scheme so as to produce electricity with the best efficiency and adequate reliability. Typically 40-50% of the load (base load) is supplied by large coal or nuclear units of the highest efficiency operating most of the year. Another 30-40% of the load (the intermediate or cycling load) is met by the utility's less modern and less efficient coal, oil and gas units as well as hydroelectric units and possibly gas turbines. Brief peak loads are met by still older fossil-fuel units and by gas- and oil-fired turbines and diesel generators. Availability of proper storage to accumulate the electricity output during periods of low demand (nights, weekends) for periods of high demand can in essence eliminate cycling and peaking units altogether, while base load plants are operating at a constant load for maximum efficiency and minimum outage time.

Renewable energy resources can be effectively utilized if the time of their occurrence can match the demand side. Because such a coincidence of supply and demand is very unlikely, particularly over short periods of time such as a day, storage becomes almost imperative. One of the most frequently encountered renewable resources, hydro power lends itself to a relatively easy solution as water can be stored behind a dam. On the other hand, solar and wind energy have to be stored in the form of heat, electricity or a chemical compound (e.g., hydrogen) to command a higher value in the energy market. For example, the economic success of the Luz solar thermal-electric power plants in the Mojave Desert in California (285 MW in operation and 350 in planning) is due to the availability of thermal storage so that the electricity can be generated to meet more closely the demand. It is also interesting to note that even though the utility grids in the U.S., because of their vast interconnections, can provide an initial storage for solar and wind electricity of up to an estimated 20% total penetration of the generation system, utilities refuse to offer capacity credits for solar- and wind-derived electricity for lack of storage at the generation site.

In the transportation sector tremendous energy savings can be realized if, for instance, the internal combustion engine is replaced by an electric motor. This requires, however, the replacement of the gasoline tank having an energy density of about 13 kWh/kg (9.4 kWh/l) with, say, electrochemical batteries the maximum energy density of which may range from 40 Wh/kg (80 Wh/l) for commercially available lead-acid to possibly 200 Wh/kg (100 Wh/l) for sodium-sulfur ones.

Energy storage systems are normally classified into five categories depending on the form and origin of the energy stored: mechanical, electrical, thermal, chemical, and biological storage.

### Mechanical and electrical storage

Mechanical storage comprises pumped hydrostorage, compressed air and flywheels. Pumped hydrostorage involves fairly large systems

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on the order of several hundred up to a few thousand MW. Because of the remote location of appropriate reservoirs from urban centers and the potential environmental implications of permanently flooding large areas, the likelihood of further significant pumped hydrostorage development in this country is very small.

Compressed air systems can vary in size from tens of MW to several hundred MW. They represent a new technology in its initial phase of commercialization (a 290 MW plant near Bremen, Germany since 1979 and a 60 MW plant in Alabama, to be completed in 1990). Although compressed air systems are not yet as efficient as hydrostorage (50% versus 70%), they have more than an order of magnitude higher specific energy density (110 Wh/kg and 8 Wh/l at 20 atm) and an inherent versatility of location compared to the latter. Efficiencies approaching 70% can be attained by improving the design of recuperators that can use the heat extracted during compression to reheat the air during expansion.

The advent of new lightweight materials with high tensile strength, such as carbon fiber, kevlar, and fused silica to mention a few, has significantly enhanced the chances of flywheels becoming practical storage systems. Specific energy densities on the order of 50 Wh/kg (60 Wh/l) are already available, albeit for specific applications because of the cost of composites (the Canadian Coast Guard is replacing the present lead-acid battery storage of photovoltaic-powered remote light stations with standardized 8.5 kWh at 23,000 rpm s-glass, carbon fiber, aluminum composite flywheels). An order of magnitude higher densities are possible with the full utilization of the new materials. Thus, composite flywheels making use of several layers of different materials to optimize energy density are compact, have efficiencies in excess of 90%, a life expectancy over 20 years and are well suited for load leveling and renewable storage of residential and small commercial buildings as well as for increasing the efficiency and/or powering of electric vehicles.

Electrical storage includes electrochemical batteries and magnetic superconducting coils. The last decade has seen the commercialization of advanced lead-acid batteries employing the so-called starved electrolyte concept, which makes use of a highly porous separator to keep the electrolyte immobilized. The need to add water is eliminated. The electrode grids are also made of a lead-calcium alloy to further enhance the life expectancy of the battery. Specific energy densities on the order of 35 to 45 Wh/kg are already available with an efficiency of 80% and over 1500 discharge cycles at 80% depth of discharge. Of all the other large energy storage electrochemical batteries, the one nearing commercialization is the sodium-sulfur battery. It can attain a 180 to 200 Wh/kg specific energy density and an 80-85% efficiency. The molten sodium and sulfur electrodes insure a very long life, although the solid beta-alumina electrolyte limits this life at present to 1000-1500 cycles. Electrochemical batteries can offer storage ranging from one kW up to several MW and as such are ideally suited for: load leveling for utilities (the largest systems in the world are a 17 MW in Berlin, Germany since 1987 and a 10 MW at Chino, California since 1988, both lead-acid of the standard open cell type), commercial and residential buildings; renewable energy storage at the residential level (thousands of photovoltaic-powered houses exist in the U.S. and around the world); and powering electric vehicles (the GM Impact unveiled in 1990 has a 13.6 kWh storage in 32 advanced lead-acid batteries with a range of 124 miles).

Electricity can be stored with very high efficiency in superconducting coils in the form of a magnetic field. This development is in its infancy, but the potential is great as it offers a direct and mostly superior substitute for pumped hydrostorage. Although the specific energy density of this system is comparable to that of pumped hydrostorage, its efficiency is about 95% (2% refrigeration losses and 3% AC/DC conversion losses), and it can respond literally in a fraction of a second to supply and demand changes. It is envisioned that standard utility systems will have a size of 1000 MW with 5000 MWh capacity, a 5 h charge of discharge time and a circular coil of 1000 m in diameter.

## Thermal storage

Thermal storage comprises the traditional sensible and latent heat storage as well as the more novel thermochemical storage. Thermal storage appears to be of paramount importance in the development of solar thermal technologies both at the utility level as well as the residential and commercial building levels. It can be also used as for load leveling in certain situations. Sensible heat storage can employ water (1.2 Wh/l°C), rocks (0.6 Wh/l°C), and other materials. For example, a specially formulated oil is used in the Luz solar thermal-electric plants at an operating temperature of 250 °C-350 °C. Iron, which has almost the same heat capacity as water, can operate at high temperatures unlike water and can transport heat much more effectively than rocks.

Of the various latent heat storage materials at ambient temperatures, calcium chloride hexahydrate is commercially available mostly for thermal storage in buildings and comes prepackaged in a number of configurations, including rods, translucent pods and steel cans. This particular material in a proprietary formulation to minimize phase separation has a phase change temperature of 27 °C, a thermal storage capacity of 48 Wh/kg (82 Wh/l), and a life expectancy of several thousand cycles. On the other hand, several high temperature latent heat chemical compounds are available. Besides storing heat, cold storage is becoming nowadays even more important. Using off-peak electricity, one can freeze (93 Wh/kg) or possibly chill water, which is then used for air conditioning, refrigeration or other related applications during on-peak electricity demand periods. Several companies are already manufacturing standardized water containers that can be used to store certain amount of cold. The typical efficiency of storing and recovering sensible and latent heat may be on the order of 80 to 90% depending on system design.

Thermochemical storage typically entails the storage of solar heat as chemical energy in materials produced by the thermal dissociation of certain compounds. The recombination of the generated chemicals will release heat at a desirable rate. Thermochemical systems operate at high temperatures and are limited to specific materials. Two proposed and studied, but never built and tested, systems involve the dissociation of ammonia (915 Wh/kg) and sulfur trioxide (336 Wh/kg). An estimated heat storage efficiency of 70% is typically quoted for thermochemical processes.

## Chemical and biological storage

Energy can be held in the chemical bonds of many compounds and released by exothermic reactions. Combustion is the most notable such reaction. Chemical energy storage is very practical for several uses, the most prominent of which is transportation, because of its high specific energy density. Two of the most important chemical storage compounds are methanol and hydrogen.

Methanol has attained preeminence because it is the feedstock material of several chemicals and most recently has been proposed as a substitute for gasoline in internal combustion engines. Methanol is made from the catalytic reaction of hydrogen and carbon monoxide both of which can be obtained readily from either coal or natural gas. Methanol can also be obtained from biomass but with considerable more complexity. The major advantage of methanol as fuel is its presumed reduction in the generation of ozone and emissions of hydrocarbons and carbon monoxide, while it appears to generate formaldehyde (which can be reduced through proper on-board catalysts). Production of methanol from coal increases the amount of carbon dioxide in the atmosphere compared to the combustion of gasoline of equal energy content, while production of it from natural gas may result in a small reduction of carbon dioxide. Methanol from biomass eliminates net greenhouse gas emissions but cannot be generated in adequate quantities to replace all petroleum-derived fuels in the U.S.

The low vapor pressure of methanol requires a 85-15% methanol-gasoline mixture for cold starts. It has been estimated that this small addition of gasoline results in only half as much reduction in ozone as that from the use of pure methanol. Hence, the impact of methanol in reducing the greenhouse effect and air pollution appears to be very small, if any at all. We may also note that there is a widespread perception, which may not be entirely correct, that methanol can easily replace gasoline with relatively small modifications in the present fuel distribution system and vehicles. It should be also noted that methanol has only half the specific energy density of gasoline (6.4 kWh/kg and 5kWh/l).

The idea of utilizing hydrogen as a universal fuel as well as an energy storage medium is not a new one. The concept of the so-called hydrogen economy has been around for two decades now. In this scenario hydrogen becomes the foremost energy carrier even more so than electricity. Although hydrogen can be generated from coal and natural gas, its true usefulness comes from being generated by the decomposition of water with the aid of renewable energy resources. The best known way of decomposing water is electrolysis. Thermochemical cycles offer another possible avenue of hydrogen generation from water, but none has ever been tried on a commercial scale. Hydrogen is the ideal fuel for any combustion process for it produces virtually no pollutants with the possible exception of nitrogen oxides in internal combustion engines (which can be nonetheless reduced to well below the emissions from a gasoline powered engine). The catalytic combustion of hydrogen, for example, in household uses totally eliminates nitrogen oxides as well. Hydrogen can be transported and distributed by pipeline like natural gas (a hydrogen pipeline has been operating in the Ruhr area of Germany since the 1930's).

Hydrogen's use as an automotive fuel presents some space problems because of its low density. Although the specific energy density of hydrogen is 38.9 kWh/kg, it is reduced to 0.4 kWh/kg (0.8 kWh/l), 1.1 kWh/kg (0.55 kWh/l) and 6-7 kWh/kg (0.95 kWh/l), respectively, if stored on-board the vehicle in a metal hydride, as pressurized gas at 200 atm, and as liquid in a proper cryogenic dewar. Prototype cars powered by hydrogen were unveiled in 1989 by Mercedes-Benz using a metal hydride storage with a 70 miles range and by BMW using a liquid storage with a 135 miles range. Another hydrogen storage possibility for automotive applications is ammonia, in which case the energy density per volume is comparable to that of gasoline. However, a temperature of 700-800 °C is required to decompose ammonia in order to obtain the hydrogen component for combustion.

The availability of hydrogen as an automotive fuel makes feasible the replacement of the internal combustion engine by fuel cells. In this case the fuel cells generate electricity to power electric motors for a far more efficient utilization of energy compared to the internal combustion engine. We may also point out the hydrogen from the reformation of natural gas, even though a temporary solution, can eliminate local pollution problems without worsening the greenhouse effect any more than directly burning the natural gas used in the generation of hydrogen. If anything, hydrogen from natural gas would lessen the greenhouse effect because the fuel efficiency of a hydrogen-powered internal combustion engine appears to be as much as 40% higher compared to gasoline due to the gaseous nature of hydrogen and its high speed of diffusion in the air mixture.

Biological storage is identical to chemical storage in principle, the only difference being that the chemical compounds are produced naturally by photosynthesis. Nature generates a multitude of organic compounds starting with water, carbon dioxide and solar radiation. However, the conversion of solar radiation to chemical energy proceeds at a very small efficiency. It is a matter of simple arithmetic to realize that at a 1% conversion efficiency, it is practically impossible to meet the energy needs of the U.S. from biological sources. However, biological sources can supply most or all the needs of selected fuel usage such as in agriculture. Moreover, biological sources can supply all our societal needs for the chemicals currently generated from petroleum. For example, a mixture of 40% soybean oil (10.8 kWh/kg, 10 kWh/l) and 60% ethanol (8.3 kWh/kg, 8.9 kWh/l), from sugar fermentation, can be used interchangeably with diesel oil in trucks and tractors. The cost of this mixture is presently $1.60 per gallon vs. $1 per gallon for diesel fuel. As another example, we can mention the use of starch either in a mixture with polyethylene or even in pure form to produce varying grades of biodegradable plastics. Again the cost of such biodegradable plastics may be two to three times the cost of the petroleum-derived products at the present time.

### Policy implications

A natural question to ask at this point is why energy storage, important as it appears to be, has not yet been implemented in a large scale. The reason is obviously not the lack of technology. For even though technical questions in several areas need to be answered, there exists plenty of practical technology waiting for implementation. It can be argued then that the major roadblock is unfavorable economics. However, one can easily find situations, such as utility load leveling, where storage is more economical than present policies. But even if energy storage technologies are presently more expensive or less convenient than the business-as-usual alternatives, there is evidence indicating that the public may support the necessary changes in the interest of protecting the environment. Thus, for example, people will be willing to fill their car tanks twice as frequently if the reward is a cleaner environment. This implies, however, that clear messages have to be sent to the public from the government and other policy-making entities saying that such changes are needed.

# NEWS

## Forum Elections

We'll have to wait until the July issue to print the results of the recent Forum election. We usually run the results in April, but this year our new election procedure, directly mailing the ballots rather than printing them in the January *Physics and Society*, was embarrassingly successful. It produced many more responses than usual, perhaps ten times as many. It's a major effort to open the ballots and count them, and the count won't be finished until after this issue goes to press. Sorry

## 1990 Szilard and Forum Awards

Both awards will be presented at the 1990 APS spring meeting, 16-19 April in Washington, DC.

*1990 Leo Szilard Award for physics in the public interest*: To Theodore A. Postol of the Massachusetts Institute of Technology: "For his incisive technical analysis of national security issues that has been vital for informing the public policy debate, especially with regard to basing modes for ballistic missiles, survivability of submarines, effects of nuclear war, effectiveness of tactical ballistic missiles, and implications of accidental launch protection systems."

*1990 Forum Award for promoting public understanding of the relation of physics to society.* To Richard Wilson of Harvard University: "For his outstanding research and promotion of public understanding on a broad spectrum of issues dealing with physics, the environment, and public health, including his work in reactor safety, estimation of hazards posed by environmental pollution, and pioneering use of comparative risk analysis."

## Newly Elected Forum-Sponsored Fellows of the APS

Caroline Littlejohn Herzenberg: "For leadership and advocacy with respect to women's participation in physics, and for contributions toward assessment of issues relating to space weaponry, and for research accomplishments in Mossbauer spectrometry."

Allan R. Hoffman: "For his many and creative contributions to analyzing and facilitating legislation and National Research Council studies on energy, science advice, and science and public policy."

Henry C. Kelly: "For his outstanding contributions to arms control, solar energy, and energy and economic policy."

Richard A. Meserve: "For his contributions at the interface of physics and society, especially for his report on safety problems of nuclear reactors at government laboratories."

Rustum Roy: "As director of the Penn State Science Technology and Society Program, and in many other ways, he has considerably improved our understanding of the interaction between science, technology, and society."

Carl Edward Sagan: "For his sustained and exceptional contributions to the public understanding of science and societal impacts of technology."

## Forum Sessions at the Anaheim Meeting

One Forum session was presented at the Anaheim meeting, held 12-16 March 1990:

*International Safeguards on Pu/HEU.* David Hafemeister, California Polytechnical State University, presiding.

- "Restricting production of fissionable materials: an historical overview," John M. Taylor, Sandia National Laboratory.
- "Realities on verifying the absence of HEU in gas centrifuge plants," David W. Swindle, Oak Ridge National Laboratories.
- "International safeguards for reprocessing *can* be effective," James E. Lovett, Lovett Associates.
- "Limiting and reducing inventories of fissionable material," Charles Hebel, Xerox Corporation.

## Forum Sessions at the Washington DC Meeting

The spring meeting, being held in Washington DC during 16-19 April this year, is traditionally the big meeting of the year for the Forum. In Washington, we'll have the Forum Awards and lectures, three invited paper sessions, a group of physics-and-society contributed papers, and our annual business session. We hope that you will attend these sessions, and that you will try to attend this meeting this year and every year.

*Forum Awards Lectures.* The 1990 Leo Szilard Award for physics in the public interest will be awarded to Theodore A. Postol of Massachusetts Institute of Technology, and the 1990 Forum Award for promoting public understanding of the relation of physics to society will be awarded to Richard Wilson of Harvard University. Recipients will give a talk following each award ceremony. Their citations are given above.

*Health Effects of Non-Ionizing Radiation.* Lynn Jelinski, presiding.

- "Interaction of extremely low-frequency electromagnetic fields with humans," Thomas S. Tenforde, Battelle Pacific Northwest.
- "Substrates of electromagnetic field interactions with biomolecular systems," W. Ross Adey, Veterans Administration Medical Center, Loma Linda.
- "60 Hz fields: problems in risk assessment and policy response," M. Granger Morgan, Carnegie Mellon University.
- "Non-ionizing radiation activities and issues," Joe A. Elder, U.S. Environmental Protection Agency.

*Science and Mathematics Pre-College Education: What Can We Do?* James Rutherford, AAAS, presiding.

- "Project 2061: possible impacts on science education," Margaret Macvicar, MIT.
- "Models for scientist involvement in pre-college education," William Aldrich, National Science Teachers Association.
- "Science education: a high-school educator's view," Clara Tolbert, Vice Principal, Central High School, Philadelphia.
- "AIP activities in science education," Brian Schwarz, AIP.

*Missile Technologies and Nuclear Arms Control.* Frank von Hippel, presiding.

- "Arms control and breakout from nuclear arms treaties," Michael I. Sobel, Brooklyn College.
- "A flight-test ban and new reentry vehicle technologies," Lisbeth Gronlund, Program for Defense and Arms Control Studies, MIT.
- "Depressed trajectories, short time-of-flight, low-burnout and fast-burn boosters," Bob Dietz, retired engineer, Lockheed Missile Division.
- "Deterrence through a comprehensive ballistic missile flight-test ban," Robert Sherman, defense specialist for Congressmen Les AuCoin and Tom Downey.

## Promote Science and Society Awareness! Inform Others About the Forum

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# COMMENT

## Strategic Instability is a Bad Buy

Strategic nuclear weapons issues seem almost passe' in these days of elections in Eastern Europe, arms control breakthroughs, withering hawk and doves, and *New York Times* announcements of the end of the cold war. But unfortunately, nuclear arsenals still threaten the globe, new first-strike nuclear weapons still threaten superpower stability, and a new $295 billion Defense budget still threatens our wallets. So continued analysis is not yet out of line, in fact may be especially in line now when things are changing so rapidly that anything seems possible.

This essay's thesis is that the United States can actually buy more military security by spending less money on several strategic weapons programs, and that this is true even when "security" is defined in the narrow, purely military, cold war sense. Looking only at the strategic part (12%) of the defense budget, we could save some $13 billion per year by canceling or reducing several programs that are not only unnecessary but are in fact harmful to national security.

Nuclear weapons, especially strategic ones, are fundamentally different from other weapons. Although most people, and even most defense analysts, give lip service to this notion, defense budgets seldom embody it. Military security, understood in the conventional sense of preventing or defeating armed attack on the nation or on its interests, is generally increased by possession of greater numbers of weapons. So arguments over non-nuclear military spending are generally over priorities: is it better to buy this weapon system, or to put the money someplace else? Nuclear weapons are different. Their purpose is to deter war, not to fight one. In a sense, they are not military weapons at all, for their actual use would defeat their purpose. So more may not be better. Sometimes more is worse.

To think about deterrence, we must ask how nuclear war could occur. Even under the most malign assumptions about Soviet (or U.S.) motives, nobody expects nuclear attack to occur on purpose, i.e. "out of the blue," like Pearl Harbor: neither side would risk it. Scenarios involving accidents and mad generals are a little more plausible. But most plausible by far is the pre-emptive nuclear strike in the midst of a crisis, out of fear of loss of control and of attack (stimulated by the same fears) by the other side. Any rational deterrence policy must be directed at preventing this scenario.

A pre-emptive strike would aim mainly at the other side's strategic nuclear weapons. So superpower "A" would be more likely to preempt in a crisis if either "B's" nuclear weapons are vulnerable to attack by A (because then A might reduce its own damage or even "win the war" by attacking B), or if A's weapons are vulnerable to B (because then an attack by B seems plausible to A—the "use them or lose them" syndrome).

It follows that, from a purely military point of view, strategic nuclear weapons should be invulnerable and should not threaten the weapons of the other superpower. Weapons that don't satisfy these criteria might be worse than useless, for they might encourage the crisis pre-emption that nuclear weapons should be primarily designed to discourage.

And it would be ridiculous, wouldn't it, to spend money on weapons that are worse than useless?

There are at least four big-bucks programs that our country would be militarily better off without even if they were free, because the weapons are either vulnerable, or they make Soviet weapons vulnerable:

- *Rail-based MX*. Its vulnerability, combined with its threatening lethality against Soviet silos, make this the world's most destabilizing weapon. Moving our 50 MXs (500 warheads) from their present silos to their planned rail garrisons will make them more, not less, vulnerable in the only scenario that matters: an escalating crisis in which the U.S. does not have or does not take the 4 hour lead time needed to disperse the MXs. With a 4 hour lead time, we can mobilize plenty of additional deterrent power without the MX. Cancellation would save over $2 billion per year for several years. The best thing to do with our present MXs is trade them away, e.g. for Soviet SS-24s or SS-18s (but not for the ground-mobile SS-25s, which are stabilizing).
- *SDI testing and deployment plans*. Space-based defense cannot prevent total destruction in a determined Soviet attack. SDI would do us more harm than good by increasing Soviet perceptions of a U.S. first-strike threat, because even a partially effective SDI might be of real benefit in defeating a weakened Soviet retaliatory strike. Thus SDI, to the extent that it works, will be destabilizing. Cutting it back to pure research, as it was before then-President Reagan's "Star Wars" speech, would save some $3 billion per year.
- *Trident II submarine-launched ballistic missile*. Although the nearly-invulnerable SLBMs are usually regarded as stabilizing, Trident II is different. Because it can destroy Soviet silos, it is destabilizing. We have plenty of stable SLBMs now, and have no need for the Trident II. Cancellation would save $2 billion per year.
- *B-2 bomber*. We have plenty of bombers. The B-2 adds no deterrent value to our existing B-52 and B-1 bomber forces. The purely deterrent mission is performed better (because more surely) with cruise missiles launched from outside the Soviet Union than with B-2s overflying the Soviet Union. There is only one task the B-2 can perform that existing bombers cannot: finding and destroying Soviet mobile missiles (although inefficiently). This task is destabilizing and thus harmful to U.S. security. Cancellation of this expensive program would save us over $6 billion per year.

Cold war fears have kept these programs alive for years, even decades (nearly 20 years for MX). This is an auspicious year to finally defeat them, because of U.S. budget pressures and because the Gorbachev era makes a less paranoid perspective possible.

You might have noticed that the ground-mobile Midgetman missile is one large strategic program that is not on my list. Midgetman falls into a different category, because its deployment would have a stabilizing effect on our currently unstable ICBM force. This is true even though the Midgetman has the unfortunate ability to destroy Soviet missile silos with high probability. Current U.S. ICBMs have this first-strike (the approved euphemism is "counterforce") ability, but they are also vulnerable. Midgetman, deployed in the "random mobile" configuration over large tracts of land in the southwest, would be essentially invulnerable. The only question about Midgetman is whether its advantages are worth the money. If we decide not to buy Midgetman or some other invulnerable ICBM scheme (there is at least one other, known as "multiple silos" or "carry hard"), then we should dismantle our ICBMs and go to a "diad" of bombers and submarines.

Beyond the increased military security, we obviously increase overall national security by saving money on these harmful big-budget programs. For a rough estimate of this effect, let's imagine dividing the saved $13 billion per year among the 50 states. Then each state gets $260 million per year. For comparison, the Governor of my own state of Arkansas recently proposed an excellent and comprehensive new education package, but the legislature defeated it on cost grounds. The cost of this supposedly exorbitant program was $200 million per year.

*Art Hobson*