• EIGHT •

Nuclear Fusion: Boundless Optimism and Limited Energy

The front page of the *Washington Post* trumpets, "U.S. Makes Major Advance in Nuclear Fusion," with the first paragraph quoting a government expert saying this "could lead to the production of the first practical working fusion reactors."[1] This was not a reference to the short-lived hope for "cold fusion," but rather to the long-standing billion-dollar government project to tame the power of the sun for peaceful use. But this headline appeared in 1978, and "working fusion reactors" remain decades away.

The *Washington Post* story was neither the first nor the last time that breakthroughs have been breathlessly announced in the effort to produce energy for electricity by the same process used in the hydrogen bomb. In the late 1950s newspapers in Great Britain wrote about early fusion research with the implication that reactors would soon be on-line.[2] In 1992, the chair of the House Committee on Science, Space, and Technology spoke of a recent "breakthrough" in fusion research while calling for continued American funding of the fusion program.[3] All of this in the face of a program that has yet to achieve "breakeven"[4]—the point where more energy comes out a controlled reaction than goes in—and a program for which the government itself now projects that commercial reactors will not go into operation before 2040.[5]

Clearly fusion has promise. Only the prospect of extraordinary benefits could sustain enthusiasm for a program that has been underway for forty years and is still more than forty years away from commercial

reality. The ready availability of fuel and the possibility of safe and environmentally sound reactors has convinced many that fusion could someday outperform not only the nuclear fission process used in current reactors, but other sources of energy as well.

Fusion may someday play a role in American energy supply, but those expecting miracles will be disappointed. Even forty years from now, there will be no magic end to legal and economic constraints on major sources of energy. In the meantime, fusion provides an illuminating view of the hazards of doing big science in a single agency and of the prospects for international cooperation. And it illustrates how even the distant prospect of limitless energy can affect our thinking about the appropriate scale for human technology.

The Underlying Science

The basic science that underpins nuclear fusion goes back more than a hundred years and displays a familiar pattern of unpredictable twists and turns.[6] Discussions of the science of nuclear power usually begin with Albert Einstein's 1907 assertion that, in theory, any tiny bit of matter can be converted into an enormous amount of energy. Although the equation $e=mc^2$ represented a quantum leap in the development of nuclear power, it is arbitrary to regard that formula as the first step. The idea that mass contains energy grew out of Einstein's 1905 paper on the theory of special relativity, which in turn drew in part on the work of the nineteenth-century Scottish physicist James Clerk Maxwell. The progressive nature of science ensures that even the most astonishing ideas have antecedents and even the most ordinary observations may have surprising consequences. Neither Maxwell nor Einstein had the slightest idea when they published their work that it would someday lead to nuclear power.

In the twentieth century the practical task of liberating energy from mass developed along two lines, fission and fusion. In 1938, uranium atoms were split by neutron bombardment, a process quickly termed *nuclear fission*. Splitting the atom left less mass than had existed before the bombardment, the remainder having been given off as energy in accordance with Einstein's equation. Fission served as the source of power for the atomic bombs dropped on Hiroshima and Nagasaki as

well as for the civilian nuclear reactors that now provide about 15 percent of the electricity in the United States.

The theory underlying nuclear fusion, the other line of development, emerged before fission, but its practical impact appeared later. As early as 1927, scientists speculated that stars, including our sun, were fueled by the forcing together, or fusing, of two lightweight atoms and this fusion diminished mass and released energy, again in accordance with Einstein's equation. The precise process that powers the stars was determined by Hans A. Bethe in the late 1930s. After World War II, the United States developed the hydrogen bomb, which uses fusion to create destructive capabilities far beyond those of the fission-powered atomic bomb.

In the 1940s, many scientists realized that fusion, like fission, might be harnessed for civilian use. The basic method of generating electricity from fusion parallels that used in generating electricity from fission, coal, or any other heat source. You begin by generating heat, which boils water, thus producing steam to turn turbines that produce electricity.

Producing heat in a controlled manner from fusion is terribly difficult. Because the nuclei of light elements are positively charged, they repel each other electrically. In the enormous gravity of the sun, the nuclei of hydrogen atoms are fused together to the point that a heavier element, helium, is formed and energy is released. On earth, we lack the sun's gravity, so scientists need to achieve temperatures many times hotter than the sun's core while containing the colliding nuclei at those temperatures for a sufficient length of time and at a sufficient density in order for significant amounts of energy to be given off. Fusion researchers discovered in the 1950s that forcing hydrogen isotopes to achieve the necessary temperatures of over 100 million degrees Celsius and the necessary densities was even more difficult than expected. At the temperatures involved in fusion, most atoms are stripped of their electrons with the result that matter becomes a mixture of positively charged nuclei, called ions, and free electrons. Matter in this state is known as plasma and behaves differently from solids, liquids, or gases. An enormous amount of basic scientific research on plasma physics has been and remains necessary for determining how to control a fusion reaction.

Research on fusion has been taking place since the 1950s in the United States, Europe, Russia, and Japan. Some of the most promising results to date took place in late 1991 when the Joint European Torus

facility in Great Britain put out about two million watts of energy, and in late 1993 when a Princeton University laboratory produced over five million watts.[7] These tests, however, lasted only a few seconds each and, more importantly, they produced less energy than they consumed.[8] Clearly scientists are still short of the "breakeven" point, where fusion produces more energy than it uses up, and they are even further away from making the reactions "self-sustaining," in other words, capable of keeping themselves going while remaining under control.[9]

Obviously, controlling fusion is an extraordinary undertaking—the head of the American program once described it as "probably the most difficult technical task that has ever been attempted, bar none."[10] But the promise at the end of the road is considerable. The most promising fuel for the fusion reaction is a combination of two isotopes of hydrogen: deuterium and tritium. Deuterium occurs naturally in ordinary water and thus supplies are far more ample than for oil and gas. Tritium, which is radioactive, is produced from lithium, another readily available substance.[11] Moreover, the amounts of deuterium and tritium in reactors would be so small that a malfunction would not cause a major calamity. If something went wrong, the plasma would strike the walls of the containment vessel and quickly cool down.[12] The waste disposal problems also seem less daunting than with nuclear fission. The only radioactivity associated with reactor operation would come from the tritium and from neutrons striking the reactor structure. Neither source is expected to be a major problem. Finally, like nuclear fission, fusion involves no fossil fuels and thus no combustion products that contribute to global warming.[13]

The American Fusion Program

Although it is now seen as a civilian energy program, the American efforts to control fusion began in secret and in the shadow of World War II.[14] Because of the wartime link between nuclear energy and national security, the Atomic Energy Act of 1946 created a nearly complete government monopoly over nuclear matters and set up a new agency, the Atomic Energy Commission, with authority over both the military and civilian aspects of nuclear power. In 1951, the commission created Project Sherwood, a secret program under which laboratories around the country took diverse approaches to the problem of controlling fusion

reactions. In 1958, the United States, the former Soviet Union, and Great Britain simultaneously made their fusion programs public.

Today, the American fusion program is run by the Department of Energy, a successor agency to the Atomic Energy Commission. Although a few other agencies play a minor role, fusion is for all practical purposes a Department of Energy operation.[15] At present, that operation is funded at a level of about $300 million a year.[16]

Science counselors have become abundant in the fusion field, as researchers have sought to avoid the sort of overpromising that was so costly to nuclear fission. It is generally politicians and journalists who talk repeatedly of fusion breakthroughs and of solving the energy crises. Dr. William Happer, Director of the Office of Energy Research in the Department of Energy, speaks cautiously of fusion as "an important, long-range element of the National Energy Strategy" and of the need "to improve the environmental and safety characteristic of fusion."[17] His most optimistic goal is "having an operating demonstration power plant by about 2025 and an operating commercial power plant by about 2040."[18]

Even with the appropriate cautions of science counselors, the regulatory gap will be a dramatic one if nuclear fusion ever enters the marketplace. Solving the scientific problems and creating efficient, self-sustaining reactions will be an impressive achievement, but it will not guarantee an economically and environmentally sound technology.

Consider first the costs of fusion energy. Every discussion of this topic begins by noting how inexpensive the fuel will be for fusion reactors. But fuel costs are only a small part of the costs of generating electricity.[19] The high capital costs of building fission reactors contributed to their decline, and fusion will face at least comparable problems. According to Robert L. Park of the American Physical Society, even if "tritium were free and we could use it tomorrow the capital costs of a fusion reactor would make it financially impossible to build in the near future."[20]

Moreover, fusion energy does inevitably involve radioactivity, and thus some public opposition is likely. The radioactivity problem will be less than with fission, and the risk may in any event be far less than numerous societal risks from nonradioactive sources. But unless attitudes change, there will be public opposition on this score.

As noted earlier, radioactivity will be created by two sources in fusion reactors.[21] First, neutrons produced in a fusion reaction will make

reactor components radioactive. The extent of this problem will depend on the type of materials used in the components. Second, the radioactive tritium used as fuel diffuses through most metals at high temperatures. Even if tritium were to escape, it is less hazardous than the radioactive materials used in fission reactors and it has a half-life of only twelve years.[22] But people do not necessarily evaluate radiation risks in that fashion. The public outcry that followed an accidental 1979 release of tritium indicates that many people fear radioactivity per se. An Arizona plant made glow-in-the dark watches and self-illuminating signs; when tritium leaked, demonstrators carried signs reading "Tritium Spells Death" and the state ultimately seized the tritium held by the plant.[23] In 1992 and 1993, similar public opposition to tritium contamination flared up in South Carolina and Arizona.[24]

To scientists, these fears may simply be irrational and thus of no consequence. But to politicians, if voters are afraid, that fear in and of itself is a reality that must be dealt with. Of course public education and discourse can change attitudes, but at any given moment public fears are an important element in the real equation of how public policy is formulated.

Alternative Approaches to Fusion

Attention now to these economic and environmental factors could narrow the regulatory gap if fusion ever entered the commercial world. There is more than one way to build a fusion reactor, and the varying approaches may not be fungible from a social point of view. A description of magnetic confinement and inertial confinement—the two basic approaches currently under study—will demonstrate some of the choices now being made and the difficulties in assuring that social factors play a role in those choices. Magnetic and inertial confinement do not exhaust the options available in bringing about controlled fusion,[25] but they illustrate the choices that lie ahead.

In any fusion device, the key problem is to build a container that can hold the plasma when it is at temperatures of literally millions of degrees. Magnetic confinement systems rely on the fact that the plasma consists of charged particles that can be contained by magnetic fields. This approach dates all the way back to Project Sherwood in 1951. The most successful magnetic confinement systems to date are the Soviet-

invented doughnut-shaped magnetic bottles called *tokamaks*, a word that comes from the Russian acronym for torodial magnetic chamber.

The alternative approach to fusion containment, one that does not use magnetic fields, is *inertial confinement*. Inertial confinement dates back not to Project Sherwood, but to the 1958 invention of the laser, a device that initially had nothing to do with fusion. Lasers generate powerful and coherent beams of light that can be focused on a spot a few hundred-millionths of an inch wide. By the late 1960s, nuclear scientists were theorizing that a laser could create fusion in tiny pellets of deuterium and tritium. This work had weapons implications and much of it was classified. But the same principles have given rise to research on civilian energy generation. Inertial confinement devices have been built in which several laser beams are focused for less than a billionth of a second on microscopic deuterium-tritium pellets. By crushing the pellet core, the intense pressure achieves very high temperatures and densities. As with magnetic confinement, fusion has been achieved, but not yet in an efficient manner.

Lasers are not the only inertial confinement system. In such systems the pulsed energy source, called the driver, can be heavy or light ion beams rather than laser beams.

The social consequences of magnetic and inertial confinement systems are not identical. Neither is clearly superior and it is difficult to project how either would look in actual operation as part of an electric utility grid. With tokamaks it will be necessary to maintain the large superconducting magnets used to confine the plasma. Lasers, on the other hand, have to be shown to be sufficiently durable to actually work on a day-to-day basis. It seems likely that a given tokamak reactor would generate more electricity than a single laser system, so depending on one's views about centralization of energy production, one system might be better than the other. As to radioactivity, it is plausible that laser systems would involve smaller inventories of tritium than tokamaks.

In an ideal world, different fusion systems would compete so that the most socially desirable option would ultimately be chosen. It may even be that some utilities would choose magnetic confinement systems whereas others would opt for inertial confinement. But the nature of the fusion research program makes it unlikely that both technologies will be available for public scrutiny.

First of all, fusion research takes place, for all practical purposes, in

one agency—the Department of Energy. As budgets have tightened, it has become impossible to fund every avenue of research. Magnetic confinement has the enormous advantage of being closer to demonstrating breakeven, or scientific feasibility—in other words, getting out more energy than you put in will probably happen first in a tokamak rather than an inertial confinement device. This result, and the likely follow-ups involving the creation of a self-sustaining reaction, will have important scientific consequences in terms of our understanding of plasma physics. It is unsurprising that scientists want to stress the most scientifically promising approach.

At present, over 80 percent of the roughly $300 million spent annually on fusion goes to magnetic confinement approaches.[26] Although there was a brief period in the 1980s when Department of Energy officials tried to foster more direct competition between magnetic and inertial confinement systems, that ended rather abruptly.[27] At present, Energy Department officials will only assert that commercialization of inertial confinement is a decade or two behind magnetic systems.[28]

In practice, of course, this means that if society ever judges fusion, that judgment will be based on magnetic confinement systems. The enormous investment, both economic and political, necessary to bring a new technology on-line has long-lasting consequences. The situation will be precisely like that with nuclear fission. Light water reactors of a particular design came on-line first and shaped public and political attitudes toward fission. The fact that many believe that alternative reactor designs available today would be superior does not mean that those designs are immediately tried out. Too many people and too many utilities have soured on fission to give other approaches a fair shot. After decades pass, a new style of fission reactor may get a hearing, but the costs in the meantime will have been enormous.

Thus fusion faces the possibility of a dramatic regulatory gap. Of course, it is possible that the first fusion reactor brought on-line will be the best possible from a societal point of view. It is also possible that inertial confinement systems, even if they are societally desirable, are simply not technically feasible. Being socially desirable does not make something scientifically possible. But there is the very real chance that we will miss out on socially promising and scientifically plausible approaches to fusion because they are not presently the leading approaches in the Department of Energy bureaucracy.

The science counselors at work in that bureaucracy have made a difference. There is far more concern today with the social consequences of tokamaks than there ever was with the social consequences of light water fission reactors in the 1950s. But a more thoroughgoing infusion of social values in the research process is not likely in the current bureaucratic environment.

The National Environmental Policy Act and Fusion Research

The current legal regime is not structured to pressure the science bureaucracy to consider alternatives to magnetic confinement more seriously at an earlier date. As we know, it is generally the case that courts exhibit great deference to decisions by the science establishment in the research phase—it is when technologies come on-line that legal norms come to predominate. There is one statute, the National Environmental Policy Act (NEPA), that, on its face and in its conception, might have altered this balance and injected a study of alternatives more forcefully into the current fusion program. But the development of the law under NEPA demonstrates once again how the views of the scientific community hold sway in American research.

The National Environmental Policy Act, passed in 1969, requires that federal agencies prepare environmental impact statements for "proposals for legislation and other major federal actions significantly affecting the quality of the human environment."[29] The references to "major" and "significantly" have been read quite broadly by the courts, so an enormous array of federal actions are subject to the statute; an early case held, for example, that building a jail triggered NEPA's requirements.[30] Moreover, NEPA requires that an environmental impact statement include an analysis of alternatives to the proposed action so that comparisons can be made.[31]

It is unclear whether Congress intended NEPA to be a technology assessment statute.[32] The language is sufficiently vague that it has fallen to the courts to give content to it through litigation. In terms of science policy, the central issue is whether NEPA could be interpreted to mean that the government has to study the environmental implications of and the alternatives to entire research programs, or whether it is sufficient to do separate and discrete impact statements on individual facilities without ever evaluating the overall program.

In the context of the fusion program, the issue plays out as follows: When the federal government builds or licenses a particular test facility, it must do an impact statement on that facility. Thus, for example, when the Department of Energy funded construction of the Tokamak Fusion Test Reactor in Princeton, New Jersey, in the 1970s, it prepared a statement analyzing the effects on the local environment of building and operating the facility, including a study of radiation releases under normal conditions and in case of an accident. The statement even discussed how the 780 people employed at the site would affect local housing conditions and school enrollment.[33]

What the statement did not discuss, however, was the overall direction of the fusion program. The Tokamak Fusion Test Reactor was just one part of a total program that included inertial confinement fusion, albeit at a lower level than magnetic approaches. Should the Department of Energy ever have to prepare a programmatic environmental impact statement for the whole fusion program, a statement that would consider, for example, the alternative of giving greater emphasis to inertial confinement approaches?

In the early years of NEPA litigation, the question of when agencies had to do programmatic impact statements was a major issue. At one time, the Court of Appeals decision in *Scientists' Institute for Public Information, Inc. v. Atomic Energy Commission* (SIPI),[34] imposed serious duties on agencies in this regard—duties that might have actually pushed agencies to at least consider issues they tend to side-step during research. The rise and fall of SIPI illustrates the limits of judicial involvement in basic science.

In SIPI the U.S. Court of Appeals for the District of Columbia Circuit ordered the Atomic Energy Commission, a predecessor of the Department of Energy, to prepare an environmental impact statement for the breeder reactor program. The breeder reactor—later largely abandoned—involved a fission technology in which the reactor, during operation, bred new fuel for other reactors. At the time of SIPI the breeder program was further along than the fusion program is today, but nonetheless it remained years away from having a direct impact on the public.

When SIPI was decided, the commission had begun building a demonstration reactor it hoped to have in operation in about seven years, and an impact statement had been completed for that reactor. The court

concluded that at some point an impact statement would also be needed for the entire breeder program; the program came before Congress every year as a "proposal for legislation" in the form of appropriation requests and it would inevitably affect the environment in the future. From the court's perspective, the fundamental issue was determining when the statement for the breeder program had to be prepared. The court thus focused on the central dilemma in controlling scientific research: an impact statement at the beginning of a research program would be meaningless, whereas a statement on the eve of commercialization would be too late. The court quoted from the trial judge's statement to counsel in the SIPI litigation to highlight the problem:

> I say this: I say there comes a time, we start out with E equals MC squared, we both agreed you don't have to have the impact statement then. Then there comes a time when there are a thousand of these breeder plants in existence all over the country.
> Sometime before that, surely as anything under the present law, there has to be an impact statement, a long time before that, actually.
> But the question is exactly where in this chain do we have to have an impact statement.[35]

To solve this problem, the Court of Appeals formulated four factors to be weighed in determining when a statement is necessary:

> How likely is the technology to prove commercially feasible, and how soon will that occur? To what extent is meaningful information presently available on the effects of application of the technology and of alternatives and their effects? To what extent are irretrievable commitments being made and options precluded as the development program progresses? How severe will be the environmental effects if the technology does prove commercially feasible?[36]

Applying these factors, the court concluded that an impact statement on the entire breeder program was necessary at that time.

The elements delineated in SIPI represent a substantial effort to guide the application of NEPA to research and development. Of course, this particular formulation could be challenged. The final factor, for example, is phrased in a seemingly negative way ("How severe will be the environmental effects . . . ?"), lending credence to the notion that technology assessment is antitechnology. It would be easy to reformulate this factor by inquiring how substantial the positive or negative environmental effects will be if a technology does prove commercially feasible.

There is no reason early analysis cannot provide a spur to certain areas of scientific research that seem particularly promising from a social perspective.

But, more importantly, SIPI represented a deviation from the usual laissez-faire attitude of the courts and the legal system to basic research. And because of the broad language of NEPA, SIPI had the potential to alter the status quo in a wide variety of areas. But the Supreme Court put an end to that possibility when it rejected the SIPI holding and thus brought NEPA into conformance with the law's usual approach to basic science.

The relevant case was *Kleppe v. Sierra Club*,[37] which involved the Department of Interior's coal leasing program in the Northern Great Plains region. In *Kleppe,* environmental groups brought suit against the Department of the Interior claiming that a comprehensive environmental impact statement was necessary to assess the government's program of issuing coal leases, approving mining plans, and otherwise licensing private companies and public utilities to develop coal reserves on federal land. The plaintiffs maintained that only by looking at the program as a whole could serious environmental analysis be done. The Court of Appeals for the District of Columbia Circuit adapted its four-part SIPI test to include all federal actions, not just technology development programs, and it concluded that enough information was already available on the overall program to do environmental analysis and that the potential environmental effects of the program were severe. The U.S. Supreme Court, however, squarely rejected the SIPI approach:

> The [appellate] Court's reasoning and action find no support in the language or legislative history of NEPA. The statute clearly states when an impact statement is required, and mentions nothing about a balancing of factors. Rather . . . under the first sentence of 102(2)(C) the moment at which an agency must have a final statement ready "is the time at which it makes a recommendation or report on a *proposal* for federal action."[38]

The Supreme Court did recognize that in some circumstances a variety of agency actions might be so closely connected to each other that it would be irrational for an agency to deny that it had made a proposal for a broad program and thus an agency would have to do a programmatic environmental impact statement. But the Court emphasized that ordinarily the question of whether an agency had to do a programmatic

statement was up to it, because "[r]esolving these issues requires a high level of technical expertise and is properly left to the informed discretion of the responsible federal agencies."[39]

Commentators swiftly noted that *Kleppe* weakened NEPA's ability to inject environmental values at an early point in the decision-making process.[40] Subsequent cases in the basic research context have hammered home the point that it is now the agency—not the courts—that decides when to take a broad look at the implications of a research program, and that agencies rarely are inclined to do that. In *Foundation on Economic Trends v. Lyng*,[41] the plaintiffs wanted the Department of Agriculture to prepare a programmatic impact statement on agency efforts to use recombinant DNA techniques to enhance animal productivity, but the Court rejected the claim, finding that the agency had discretion in this area and the plaintiffs were inappropriately using NEPA as a political weapon to try to force the Department of Agriculture to reevaluate its research priorities. In a similar case, the Court rejected efforts to force the National Institutes of Health to analyze its overall program on the release of genetically engineered organisms into the environment.[42]

Finally, the Supreme Court has squarely rejected as well the alternate theory under which the Court of Appeals in SIPI had imposed a duty to do a broad environmental study—in *Andrus v. Sierra Club*[43] the Supreme Court held that Congress did not intend to reach through NEPA appropriation requests as "proposals for legislation" or "proposals for . . . major Federal actions."

The net effect is that courts will not be in a position to force the Department of Energy to do a programmatic environmental impact statement on the nuclear fusion program. When and if such a statement is done is almost entirely within the control of the agency, as is the scope of any statement that might be prepared.

Now NEPA is simply a statute, not a part of the Constitution. Congress could amend it to both require that agencies do impact statements when the four-part SIPI test is met and to empower courts to engage in searching review of whether agencies are following that mandate. But that is not going to happen. The Supreme Court's rejection of SIPI was hardly idiosyncratic. It fits with our overall societal judgment to leave policy decisions relating to basic research with the scientist-dominated

agencies that conduct that research. Neither Congress nor the courts are likely to second-guess the potent combination of bureaucratic and technical expertise that an agency represents.

Funding Problems for Fusion

So the Department of Energy fusion program plows ahead with its focus on the tokamak. But freedom from oversight on tokamaks versus lasers does not translate into massive funding for the program as a whole. On the contrary, the fusion program has proven to be enormously vulnerable to the budgetary constraints that have marked federal policy since the early 1980s. The Department of Energy's annual fusion budget has dropped from over $500 million a year in 1980 to about $300 million at present, a tremendous cut when inflation is taken into account.[44] A particularly telling blow was struck in the early 1990s when the department cancelled plans for the $1.8 billion Burning Plasma Experiment, which was to have been the next major step in the tokamak program.[45]

Several factors have combined against fusion. First of all, the promise of distant payoffs cannot be sustained forever. When a research project seems always to be decades away from commercialization, support will erode. There are benefits to pure science in learning about fusion, but fusion has always presented itself as an energy program first and foremost. Some observers have argued that because it is so unlikely that we could maintain political support for fusion at the level and for the time necessary to produce commercial electricity, the program should be halted.[46]

Moreover, fusion has all of its eggs in one basket—the Department of Energy. Most American science is spread around among numerous agencies, a prudent system in times of tight budgets. This is how science spending generally weathered the 1980s, when a rise in defense-related research offset declines elsewhere. As a big science project centered in one agency and in a few large facilities, fusion also has been cut off from broader support in the community of university scientists.[47] It runs the risk of congressional termination in a single vote—the fate of the superconducting supercollider.

Fusion's rough road politically demonstrates the need to refine the usual division between "big science" and "little science." The Human Genome Initiative is big, in the sense of involving millions of dollars in

the pursuit of a single goal, the mapping of the human genome. But the work is spread among many universities, the funding comes from several agencies, and a variety of disciplines, including molecular biology and computer sciences, are involved. Fusion is big, but it is also monolithic. It has increasingly become a single program in a single agency emphasizing a single technology. As such it is a sitting duck for budget cutters.

The reaction of the fusion community to these fiscal problems has been dramatic. The major focus of the program has shifted to a multinational project, the International Thermonuclear Experimental Reactor (ITER). Begun in 1987, ITER is a joint effort by the European Community, Japan, Russia, and the United States to build the largest and most powerful tokamak in history. All four powers have long supported fusion research; indeed, a European tokamak, the Joint European Torus (JET), has enjoyed considerable success. The American fusion community now places great stress on our involvement in ITER.[48]

There is a certain irony here. For decades, in fusion and elsewhere, American science was supported in part on the grounds that we wanted to lead the world, both because of the cold war and for national pride. With the cold war over and budgetary constraints making pride a bit expensive, we now look for other nations to share the financial burden.

There certainly are positive features in this development. If we can spend less money, but end up in the same place technologically, the nation is well served. And working with Europe, Japan, and the former Soviet Union on peaceful projects builds ties that can help international relations generally.

But ITER is no panacea. Even reduced budget requests will continue to come under scrutiny, and the American willingness to spend substantial money for many years on a project in which we are not the unquestioned leaders is uncertain. Moreover, the problem of distant payoffs remains. ITER is still in the design phase; actual construction is years away. If it is built and works to perfection, its supporters say that the next step would be construction of a demonstration reactor, "perhaps within the next three decades."[49]

The Solar Comparison and the Dream of Limitless Energy

So the ability of fusion to provide electricity to our homes remains very uncertain. But fusion has nonetheless already provided fuel for the

formation of American values and expectations. Fusion is invariably presented as a potential godsend for our energy needs, and, as such, it plays a role in a familiar story. The scientists' belief in endless progress becomes a central theme in our consideration of our future.

The sharp debates that have already taken place over the desirability of fusion do not undercut this reality, because those debates are invariably in terms of other wondrous technologies that are said to be preferable to fusion. The usual candidate is solar energy. Thus Department of Energy fusion officials are often asked whether their program could compete with "a cheap, efficient solar cell."[50] With solar energy, we are always told, the fuel is free. But as fusion itself illustrates, fuel costs are a small part of total energy costs. A closer look at solar energy reveals the persistence of the American faith in progress.

Solar energy takes a variety of forms. For the production of electricity it is usually associated with the photovoltaic cell. Photovoltaic devices are among the most attractive forms of solar energy because they convert sunlight directly into electricity. Photovoltaics may someday play a central and desirable role in our energy picture, but they are no more magical than fusion reactors. Indeed their development follows the pattern we have seen before and they will face the same challenges as other energy sources.

First of all, the initial development of photovoltaics demonstrates the unplanned nature of scientific progress.[51] In 1839, Edmund Becquerel, a French scientist, observed that when light fell on one side of a certain type of battery cell an electric current was produced. Neither Becquerel nor anyone else could explain this "photoelectric effect." In this century, scientists came to understand the effect in terms of atomic structure—when a photon of light strikes an atom, it can be absorbed by electrons with the added energy driving off one of the atom's outer electrons. The stream of electrons set free in this fashion forms an electric current. In the early part of this century scientists used this knowledge to build the first simple photovoltaic cells. The cells, made of selenium, were so costly and inefficient they had no practical use.

In 1954, researchers at Bell Laboratories accidentally discovered that certain silicon devices produced electricity when exposed to sunlight. Bell Labs pursued the matter because it was interested in finding a way to generate electricity for telephone systems in remote areas not con-

nected to power grids. It turned out that silicon solar cells were much more efficient than selenium. Still the cost of generating electricity with silicon cells was enormous compared with conventional methods. It looked as though photovoltaic devices were again going to be without practical use, and research slowed.

At this point, as is so often the case with basic research, the federal government began to play a major role. Scientists working on the space program needed a power source for satellites. Silicon solar cells filled the bill, particularly because twenty-four-hour sunlight is available in space. By the late 1950s, satellites had solar cells and the National Aeronautics and Space Administration (NASA) had begun funding research into photovoltaics generally.[52]

Today federal support for photovoltaic research continues in several agencies, including NASA and the Department of Energy. Although some photovoltaic devices are in use in remote areas and in demonstration projects, costs are still too high for routine residential use.

Thus research continues on several fronts. There is basic scientific work aimed at a better understanding of the fundamental properties of photovoltaic devices, and there is more applied work aimed at improving production of existing types of devices.[53]

On the surface, photovoltaic devices may seem like an unlikely candidate for the regulatory gap. After all, solar energy is generally described as nonpolluting and inexhaustible. President Carter, for example, said that "[e]nergy from the sun is clear and safe. It will not pollute the air we breath or the water we drink."[54] If costs come down, won't photovoltaic devices march unimpeded into the marketplace?

The short answer is no. President Carter's quote is similar to President Eisenhower's 1953 statement about nuclear energy: "peaceful power from atomic energy is no dream of the future. That capability, already proved, is here—now—today. [With adequate material] this capability would rapidly be transformed into universal, efficient, and economic usage."[55] Just as nuclear fission and fusion do not get a free ride, photovoltaics will not either.

Consider the matter of pollution. Silicon cells remain the leading type of photovoltaic device. Large-scale production of silicon cells would not be entirely benign. It is well-known that exposure to silicon dust, smoke, or fumes poses a health hazard. In particular, inhalation of silicon smoke

leads to silicosis, a chronic lung disease. When silicon is present on a small scale, as in glass blowing, the problem is handled by using adequate exhaust ventilation. Large-scale production of silicon cells, however, could mean that exhaust would have an effect on air breathed by the general public.[56]

Other materials used in silicon cell production also could raise problems. Small amounts of boron and phosphorus, which are highly toxic, are used. Freon, used in the cleaning of silicon cells, has raised environmental problems in a variety of settings.[57]

Researchers, seeking higher efficiency for photovoltaic devices, have developed alternatives to silicon. But the leading alternatives do not do away with environmental problems. Cadmium sulfide cells, which are relatively inexpensive to manufacture, rely in part on cadmium, a toxic element that often accumulates in the body, leading to kidney or liver problems. Gallium arsenide cells, which are highly efficient, rely in part on arsenic, which is not only poisonous, but potentially carcinogenic.[58]

None of this means that photovoltaic energy is an environmental disaster. The dangers may well be controllable and they may be far less than the dangers from other ways of generating electricity, including fusion. The point is simply that photovoltaics will not get an exemption from the regulatory gap when they enter the commercial world. Painful and controversial calculations concerning threats to life and health will have to be made. And if a casual approach to photovoltaic safety is taken, the regulatory gap will take its toll. The Occupational Safety and Health Administration, the Environmental Protection Agency, and other regulatory mechanisms are already in place, and thus photovoltaics will automatically be subject to searching review when widespread commercialization begins. Fortunately some science counselors have undertaken to narrow the gap; researchers at Bell Laboratories and at federal laboratories have begun environmental assessments of photovoltaics.[59]

This is not to say that photovoltaic cells and nuclear fusion are comparable sources of electricity in the sense that one could simply add up the costs and benefits and pick a winner. There is a fundamental difference in that solar cells could be placed individually on houses, whereas fusion power would be centralized and then linked to homes by a traditional electricity grid. To use Amory Lovins's influential terminology, solar energy offers the possibility of a "soft" path to our technological future, whereas nuclear takes us down the "hard" path.[60]

Now to some, this is a distinction without a difference—they want reliable electricity at the lowest cost with the fewest environmental problems, and whether the source is on the roof or at a plant miles away makes no difference. But to others, the soft versus hard path debate has important political and cultural implications relating to the centralization of governmental power and citizens' sense of control over their lives. Thus Lovins himself, as early as 1976, described fusion as a "complex, costly, large-scale, centralized high-technology way to make electricity—all of which goes in the wrong direction."[61] Of course, the hard path has its supporters as well, because to some putting an energy source on a rooftop is a nuisance and a recipe for an unhealthy relationship between an individual and the community.[62] Moreover, when your energy source is on your roof, your neighbor's decision to plant a large shade tree takes on new consequences. American courts and legislatures have only begun to work out when homeowners should be able to prevent their neighbors from cutting off access to the sun.[63]

Similarly, widespread use of photovoltaics on residential rooftops will raise issues concerning the structure of the energy distribution system. Should individual homes receiving electricity from the sun be required or allowed to hook up with traditional power grids? How should electric bills be determined when individuals want to be linked to the grid at all times but only use it when their solar system is inadequate?

So, in the end, solar energy, like fusion, will emerge as something less than an instant solution to our problems. But we still hear references from groups like the National Academy of Sciences to solar and fusion energy as offering "the potential for indefinitely sustainable energy supply. That is, each could supply up to ten times our present energy requirements for thousands of years (or much more)."[64] And whereas the academy goes on to discuss the economic and other choices that have to be made, the image of endless plenty is left.

There is and should be a place in American culture for images of endless progress. But we are enriched as well by images that portray our limits. Years ago, E. F. Schumacher, drawing explicitly on the Sermon on the Mount, urged us to remember in the context of our energy debates that "we are poor, not demigods. We have plenty to be sorrowful about, and are not emerging into a golden age."[65] This turned out to be more prophetic than a bushel of headline stories on energy "breakthroughs." Our sense of who we are should draw on human frailties as

well as human potential. Keeping such ideas in mind has nothing to do with an establishment of religion; it has everything to do with a more rounded sense of who we are. As research moves on, life may become easier in some ways. But, the human condition is not something to be cured by technology.