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For Lillian

and in Memory of Max

progress in coming to grips with some of the challenges posed by the energy crisis but we face the danger of becoming quiescent when there is still a great deal that must be done. Among the items high on his agenda for action are the need to redress the burden on the poor created by higher energy prices, the need to pursue a more aggressive program of energy conservation, and the need to clarify public and private responsibilities in research and development and then strengthen the R&D process. Whether or not one agrees with the specifics of Thompson's agenda, it is difficult to quarrel with his analysis that in recent years we have walked away from any coherent energy policy while "muttering the mantra of free market," or with his warning that we can't afford to wait for the next shoe to drop.

The Politics of Energy R&D is essential reading for anyone who wants to understand the incredible tragedy of failed opportunities to permanently relieve our dependence on imported oil and to understand the waste of billions of taxpayers' dollars on uneconomic central station electric power options. The book also makes an important contribution in explaining the huge potential of more sound energy R&D alternatives - and the total failure of the Reagan administration to learn anything from the mistakes of the past or to develop the great potential of conservation and renewables for the future.

The Origins of the Nuclear Power Fiasco

Amory B. Lovins

The federal commitment to civilian nuclear power has achieved six things which are individually noteworthy and collectively extraordinary.

First, it has cost the taxpayer upwards of $70 billion (1983 dollars) in direct federal support and subsidy to bring the technology to a state where it can be commercially deployed and to bring that deployment to its present state of disarray (updated from Battelle Pacific Northwest Laboratories, 1978).

Second, the federal commitment has led the electric utility industry to allocate great sums of capital to reactor construction - over $125 billion so far, which is more than the entire cost of the space program or the war in Vietnam (Cook, 1985). In 1982 alone, utilities spent twice as much money building reactors as the nation invested in the car, truck, iron and steel industries put together.

Third, the nuclear commitment has slowed the resolution of the energy problem more than has any other federal action, with the possible exception of price regulation on natural gas. This is because money spent on slow and costly ways of replacing oil, like building power plants, cannot be spent on rapid and relatively cheap ways of saving oil, like weatherizing buildings or making vehicles more efficient.

Fourth, nuclear power has gravely undermined national security (on which another branch of our government is spending about $10,000 a second), both by spreading bombs and innocent disguises for bomb programs around the world (Lovins and Lovins, 1981), and by putting very large inventories of radioactive materials upwind of many of our cities (Lovins and Lovins, 1982).

Fifth, this commitment has engendered financial disaster for the utility industry; the Washington Public Power Supply System default of potentially $8 billion is just the overture to what Bupp describes as "a disaster of ever-growing proportions" (quoted in Cook, 1985). There has been nearly $20 billion worth of reactors written off recently as uncompletable, unneeded or both. There is another $40 billion or so about to be written off. Something like an additional $60+ billion of excess costs must be paid to operate those plants which are now under construction and may be completed, compared with the cost of not running them and using coal power instead (although coal is too expensive to be the right competitor) (Lovins, 1985a and b).

Sixth, the federal commitment to nuclear power has yielded reactors which in general cost less to write off once they are built than to operate, and which collectively are now delivering to the country about half as much energy as wood (Lovins, 1985a and b). Altogether, the damage bill comes to over $200 billion; and the bills still to be paid for cleaning up the mess - decommissioning, waste management, uranium mill tailings, and so forth - will be of similar magnitude, assuming we can find technically and politically acceptable ways to do those tasks at all.

One can fairly describe the state of the nuclear industry as the greatest collapse of any enterprise in industrial history. The nuclear industry has indeed largely succeeded in bankrupting its only possible customer, namely the electric utilities. Rarely has so much been spent by so many for so little.

I would like to offer a personal view of the structural and conceptual errors which have led to this stupendous national potlatch - and which, if not perceived and corrected, may well lead to repetitions in agriculture, security, and other policy arenas.

Historic Roots

Nuclear energy was born with its military face uppermost, and that has influenced the development of the technology in subtle ways, not least of which is the psychology of guilt. Some people who know a lot more about the institutional history than I do have remarked that we are unlikely ever to get a sensible nuclear energy policy until everybody who was involved in the Manhattan Project has died or retired. But the flip side of this is that the Manhattan Project brought together an unprecedented concentration of technical genius which was able to do remarkable things. That very achievement led, I think, to a sense of hubris which arose from a quite justified admiration for those technical accomplishments. To this day, I think that one of the most common errors made by nuclear power advocates is to assume that there are more people of high quality available in the nuclear business than there actually are. If you spend your life at a place like Oak Ridge National Laboratory, it is natural to assume that good technical people are equally available in the Munchkinville Power Company, and that there are centers of excellence of at least the caliber of Oak Ridge which can be built in many places and which can continue to operate at that technical level indefinitely. Moreover, both in its self-enforcing assumptions and otherwise, a coherent group of people often behaves in almost tribal ways in which its members, free from peer pressure, would not dream of behaving individually.

Preoccupation with what this extraordinary group of people had been able to do in the Manhattan Project has led to the systematic exclusion of other options. In fact, as recently as 1972 the Atomic Energy Commission (AEC) was arguing that it would be wholly premature to commit $15 million to solar research - an amount far less than, for example, the Paley Commission had recommended to President Truman 20 years earlier - on the grounds that the AEC and other executive agencies considered solar energy speculative and too far in the future (JCAE, 1972a: 1141). It was necessary to concentrate on options which were proven and available. Of course, that leads to the obvious "catch 22" that the only options which are then available are the ones on which you spent all the money and expertise. (Yet ironically, since 1979, actual net orders have totaled *minus* 65,000 MWe for coal and nuclear plants but *plus* over 45,000 MWe for renewables and for fossil-fueled, decentralized cogeneration.)

Bupp and Derian (1978) have explained the history of nuclear development in the following way. Originally, the private sector was not interested in building reactors. There were several stages of increasing effort by the AEC to force private industry to build reactors, and those efforts eventually succeeded. As far as I know, no nuclear vendor in the world has made money selling reactors - although some of them have managed to turn a profit on their nuclear business by making more on repairs and fueling than they lost on construction. It was not, of course, supposed to turn out that way. Bupp and Derian describe particularly well the process of "mutual intoxication" by which the AEC, the vendors, and the utilities persuaded themselves and each other that this was just another way to boil water: it would be very straightforward, and it would be very cheap.

It would generate electricity more cheaply than coal plants, which in those days were far cheaper than they are now. The two main vendors, General Electric and Westinghouse, were essentially both cowed into entering the marketplace by the threat of a nationalized nuclear TVA, and tempted into it by lavish subsidies. They built some plants as loss leaders, allegedly to lay the foundation for a gigantic nuclear power market: Westinghouse alone reportedly lost over a billion dollars. Unexpectedly and persistently, loss leaders have since become the norm for this "market."

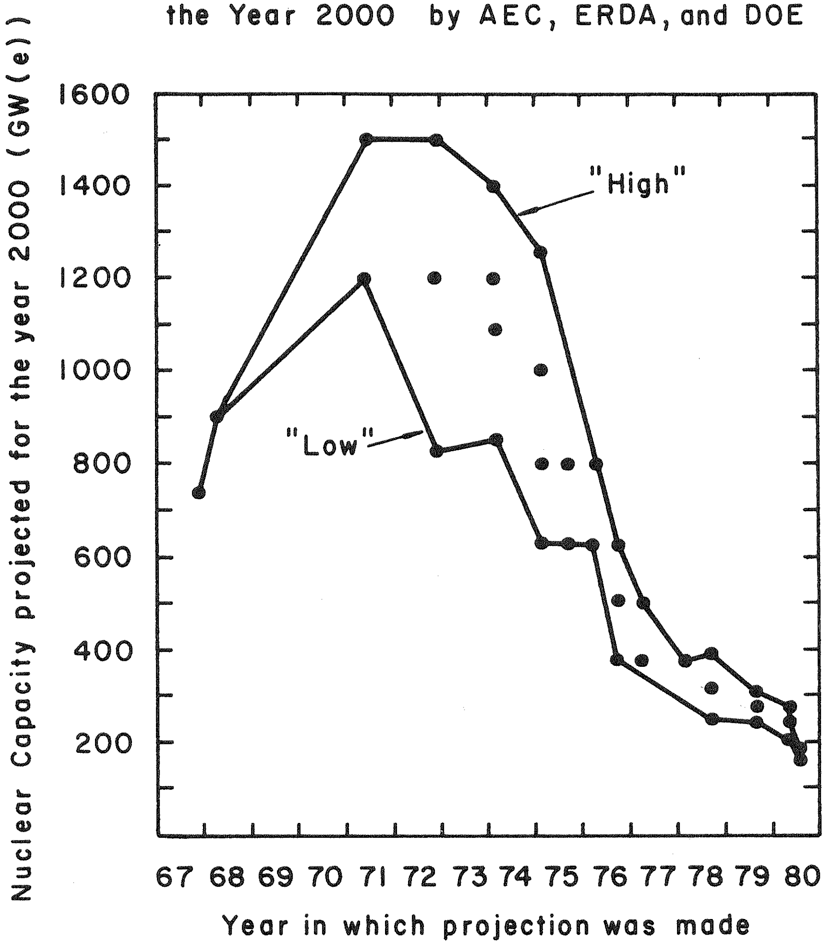
Looking back at the history of that period of "mutual intoxication" which led to the "great bandwagon market" for reactors, only Philip Sporn, among all the senior people in the utility industry, was skeptical enough to challenge the economic assumptions of nuclear advocacy (Bupp and Derian, 1978). All of his colleagues, in what had been a very conservative industry based on real engineering experience, simply took leave of their senses in a way that is really hard to understand in retrospect.

What has happened since that time is, if anything, worse. Figure 1 relates forecasts of installed nuclear capacity, made by various government agencies for the year 2000, to the year when the projection was made. From 1973 to 1980, there was roughly an eight-fold collapse of nuclear expectations. By now it is upwards of ten-fold; and interestingly enough, as Figures 2 and 3 illustrate, the pattern of collapse is identical throughout the world's market economies, over an enormous range of political and regulatory conditions - even in Canada, with no regulatory obstacles to building reactors, and in West Germany, with unregulated utilities. Part of the institutional setting in which it was possible to forecast in the early 1970s - just 13 years ago - that there would be about 1,200 to 1,500 large reactor-equivalents operating by the year 2000 was, of course, the AEC's charter, which established the agency to regulate *and* promote nuclear energy for both military and civilian purposes.

The AEC fissioned in 1974 into the Nuclear Regulatory Commission (NRC) and the Energy Research and Development Administration (ERDA). ERDA then fused with a number of bits and pieces of other agencies in 1977 to create the Department of Energy (DOE). The old AEC was then reconstituted in all but name in 1981. The cast of characters remained much the same throughout and, therefore, so did the perceptions which drove the federal institutions. As a result, an *electronuclear* elite has dominated U.S. energy policy for several decades - and still does. In fact, it is stronger now than it has been

Figure 1

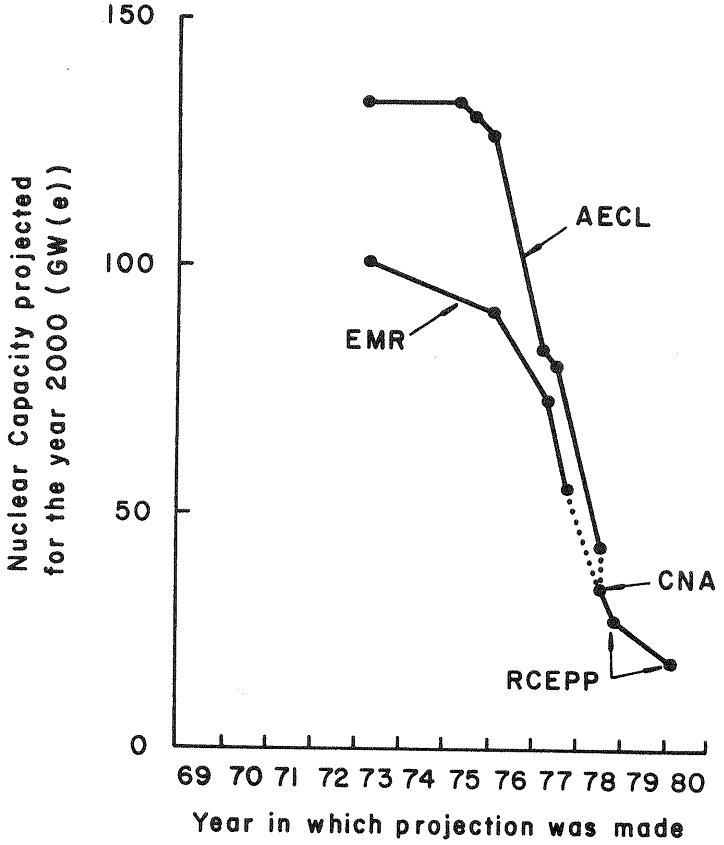
U.S. Nuclear Capacity Projected for the Year 2000 by AEC, ERDA, and DOE



Sources: Energy Information Administration (EIA) forecasts; and C.F. Zimmerman and R.O. Pohl, 1977, Energy 2:465-471.

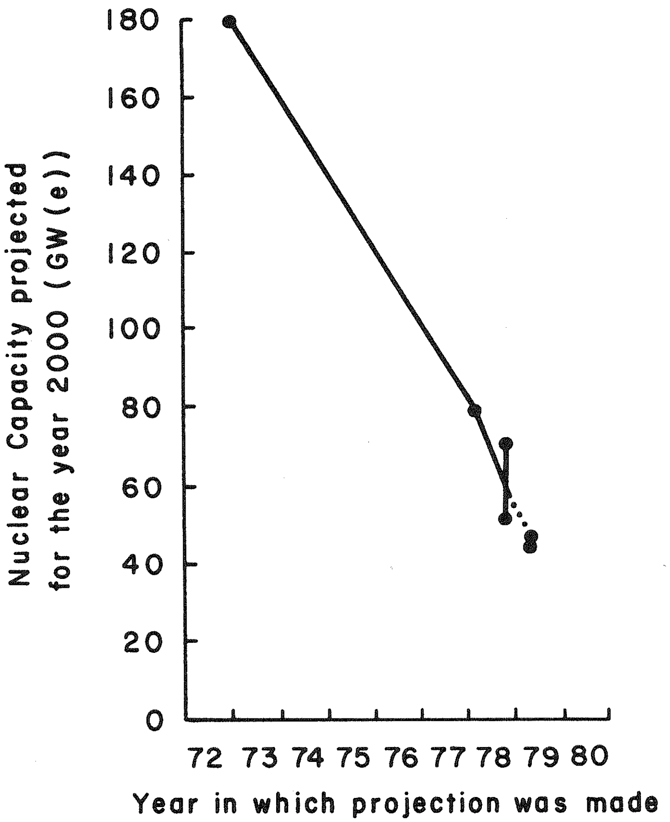
Note: Forecasts after 1978 are from the EIA supply model which calculates the maximum capacity physically achievable if constraints of demand, plant siting and construction finance are ignored. Because the pre-1978 forecasts by Zimmerman and Pohl are based on the number of likely plant orders (as opposed to the physically achievable maximum), the 1978-80 forecasts exaggerate nuclear potential relative to earlier forecasts.

Figure 2
Official Canadian Nuclear Power Projections for the year 2000



Sources : Atomic Energy of Canada, Ltd (AECL); Department of Energy, Mines and Resources, Canada (EMR); Canadian Nuclear Association (CNA); and the Royal Commission on Electric Power Planning (RCEPP).

Figure 3
Projected Federal Republic of Germany Nuclear Power Capacity in the Year 2000



Sources: Through 1978, official forecasts of the Federal Republic of Germany. The 1979 forecast was prepared by U.S. experts participating in the International Nuclear Fuel Cycle Evaluation (INFCE).

for a decade, even though it is powerless to reverse the economic trends I will describe later, which leave this country with fewer reactors committed now than it had in 1972, and the world with the fewest nuclear starts in 1984 since 1968.

Another important institutional feature of the 1960s and 1970s which carried over into the modern Department of Energy is the preoccupation with the mission of making bombs for the military. The reason bomb-making is in DOE is that the civilian government does not want to put bomb-making in the Department of Defense, but no one is quite sure where else to put it. Historically, of course, the relationship grew out of the practice of military facilities' being owned and operated by the Atomic Energy Commission. The reasons for maintaining this practice now have more to do with public policy than with administrative convenience. The preoccupation with bomb-making - which accounts directly for 60 percent of DOE's FY 1985 appropriation - has created a deep structural flaw in DOE. It means essentially that any Secretary of Energy must be acceptable not only to the lawmakers, but also to the military. This almost guarantees that the person assuming office will reflect a number of mindsets which make it very difficult for the department to develop and follow sensible civilian energy policies.

The source of the problem is not only an insular and elite bureaucracy. The Atomic Energy Commission was pushed hard to do many of the foolish things it did by the Joint Committee on Atomic Energy in the Congress, a committee of extraordinary power and cohesiveness. The Joint Committee was symbiotic, indeed the Congress still is in many ways symbiotic, with what is arguably one of the two or three most powerful lobbies that exist - the utility-industry lobby. By some counts, there are several full-time utility lobbyists per Congressional member; and, of course, the industry's lobbying base and constituency run back into everybody's district. The utility industry has annual revenues of over an eighth of a trillion dollars. Combine this economic power with the tradition of secrecy in the military and the civilian nuclear business, and the arrogance developed by people who exercised power for many years without being accountable, and you have an excellent vehicle for making mistakes on a truly grand scale.

The promotion of myths became a central function of the bureaucracies that were themselves nurtured by the myths. Let me give four examples of how that process works.

First, there are the industry comparisons which purport to show that it is cheaper to generate nuclear than coal-fired electricity. Most

of those numbers - which absolutely pervade the literature and are quoted by everybody, including the federal government - trace back to a series of annual surveys done by the Atomic Industrial Forum (AIF). A few years ago, Charles Komanoff, an independent economic consultant in New York, dug into the data base and found it was enormously skewed. The AIF choice of plants for that allegedly objective survey left out all the worst nuclear plants and nearly all of the cheapest coal plants. In fact, it left out more coal plants than it counted. There were a number of arithmetic and methodological errors as well. Komanoff showed that when all plants are counted on both sides, nuclear plants have sent out costlier electricity than contemporaneous coal plants in each year since about 1975, and that this margin has been rapidly increasing (Komanoff, 1980).

A second example concerns capacity factors, which are very important for evaluating the economic viability of something as capital-intensive as a power plant. It had been standard procedure to assume that nuclear plants would send out 80 percent of their full-time/full-power output. Some utilities still assume 75 percent. The empirical number for all large reactors in the U.S. to date is a little under 55 percent and is probably falling. When it was pointed out by the late David Comey (1974: 23) that the plants were not nearly as reliable as expected, the federal government simply redefined the norm in good Soviet fashion by inventing something called "maximum dependable capacity" - which is how much the plant can send out on the hottest day of the summer - and re-evaluated all the capacity factors on that basis rather than using the original design rating by which the plants had first been justified. (Similarly, the Edison Electric Institute has lately been so embarrassed by national reserve margins in the vicinity of 40 percent that it has started using instead a similar-sounding ratio which divides excess capacity - peak capability minus peak load - not by the peak load but by the peak capability, which is a larger denominator. Presto! The overcapacity sounds much more modest.)

A third case involves the well-known statistic that the coal fuel cycle, with its air pollution and other problems, is more dangerous publicly and occupationally than the nuclear fuel cycle. The American Medical Association, among others, has published a comparison of this kind. But these comparisons fail to include risks after 30 or 40 years. Of course, that omission disproportionately emphasizes risks associated with coal, where most of the damage is short-term (e.g., a prevalent health risk is emphysema, which typically appears relatively early after exposure). Conversely, nuclear power is made to appear attractive because nearly all of the officially calculated risk is from radon from mine tailings, carbon-14 from reprocessing, and other long-term hazards. Ramsay and Russell have examined the official surveys that are considered authoritative by proponents of nuclear power, such as the Rasmussen Report on reactor safety and the EPA fuel cycle analyses (1978: 387-403). They assumed that those studies were right, ignored climatic and proliferation risks as unquantifiable, and calculated the total public and occupational risk of the coal and nuclear fuel cycles as a function of discount rate. If future deaths are discounted at 5 percent per year, then risk is effectively ignored after a few decades and nuclear appears to be about ten times as safe as coal. If, however, a zero discount rate is employed, as is theoretically and morally required - that is, weighting long-term harm as being as important as short-term harm - then the result reverses by *three orders of magnitude.*

Finally, there is the notion encouraged by the utility industry and the federal government that the high burn-up plutonium made in power reactors is incapable of being used for powerful or reliable bombs. This has been known in the weapons community to be false since at least 1962, when a Los Alamos test settled the matter empirically. Its falsity was widely noted in the open literature by leading bomb designers during the 1970s; yet it remained the basis for U.S. nonproliferation policy throughout the period. In a review article in *Nature,* I sought to expose this myth and dispose of the matter; yet the same myth persists to this day in some rather high circles (Lovins, 1980b). The upshot of this kind of myth-making is that the nuclear establishment has succeeded in concealing the truth even from itself, and hence has spread "civilian" bomb kits around the world in the erroneous belief that bombs could not hatch out.

A side-effect of such self-delusion, incidentally, is that the Reagan administration - the most outspokenly pro-nuclear in American history - probably believes sincerely that it is helping its favorite technology. My own perception is that President Reagan and his Department of Energy have contributed signally to the irreversible meltdown of the industry's public credibility: as Mark Twain remarked, "A cat which sits on a hot stove lid will not do so again, but neither will it sit on a cold one." In one of the more bizarre instances, the industry orchestrated the President's remark that nuclear power was "hamstrung" by inept regulation, and instantly splashed the quotation across the nation in preset full-page ads. Commissioner Gilinsky of the NRC, however, pointed out to the American Nuclear Society that such an attack on the regulators did not seem to him very smart: the public, he said, may not trust the NRC very much, but they don't trust the industry at all, and if they come to believe that the NRC is incompetent, they'll conclude, not that nuclear power should be regulated less, but that it's even more dangerous than they thought. He was shortly proved right.

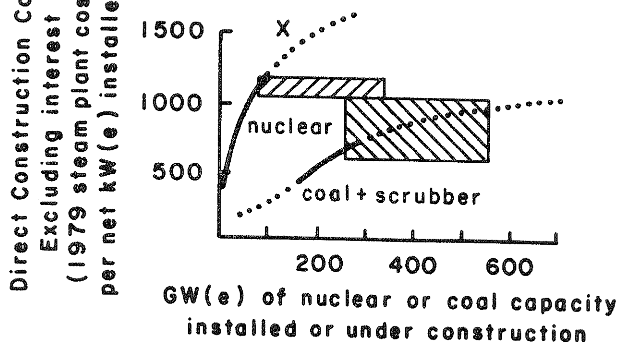
Economic Myths

Nowhere are the consequences of nuclear myth-making more clearly evident than in the economics of nuclear power. Although the future cost of nuclear electricity depends on some fourteen major and thirty-odd minor variables, all of which are disputed and many of which are highly uncertain, capital cost is the most important single variable. There has been a series of very detailed studies over many years by the AEC and its successors, and by major nuclear contractors, of how much it would cost to build a reactor in constant dollars per installed kilowatt (EIA, 1982: 34). Those studies have all been wrong, quite often by factors of 3 to 8 - very large numbers. Komanoff again happens to have assembled the empirical data and painstakingly discounted and deflated everything to constant 1979 steam-plant dollars per installed kilowatt (Komanoff, 1981). He finds a supply curve looking like that given in Figure 4. The solid portions of the curve represent all of the nuclear and coal plants commissioned between 1971 and 1978 in the United States. The dotted curves represent an extrapolation of those trends, if moderated. The crosshatched areas represent the Department of Energy's official assumptions about what will happen. The "X" represents what was actually happening in the nuclear sector as of mid-1983, in contrast to coal where the data have tended to track the dashed curve quite closely. Notice what is happening here. The real cost per kilowatt for both kinds of plants is increasing with the number of plants built or being built. This is a classic economic supply curve. It is upwardly monotonic. That was not supposed to happen. The real cost was supposed to be constant or indeed to decline as a result of supposed learning effects.

What seems to be happening can be summarized by a hypothesis which was developed by Bupp et al. (1975) and later refined by Mooz (1978) and Komanoff (1981) in collaboration with Vince Taylor. Normally if people think an activity is hazardous, the market signals that perception through things like insurance premia and tort liability. In the case of coal plants, the signaling is done at least in part through the Clean Air Act (an unintended side-effect of which, incidentally, is acid rain). In the nuclear case, however, the signals are largely suppressed by the Price-Anderson Act, which sets an absolute ceiling on liability for nuclear accidents.

Figure 4

Empirical Supply Curves for U.S. Central Power Stations



——— Actual costs for plants commissioned during 1971-78. Real capital costs per kW rose 142% (13.5% per year) for nuclear plants and 68% (7.7% per year) for coal plants. Both figures refer to construction costs prior to the Three Mile Island accident.

.... Projection from Komanoff's multiple regressions. Nuclear projection is based on data for all nuclear plants during 1971-78 (R^2 = 0.93). Coal projection is derived from 116 comparable coal plants as defined by Komanoff (R^2 = 0.68).

X Average mid-1983 completion cost estimate by utilities engaged in construction of nuclear plants.

▨ U.S. Department of Energy Electricity Policy Project assumptions (1983).

Sources: Charles Komanoff, 1981, Power Plant Cost Escalation: Nuclear and Coal Capital Costs, Regulations and Economics; and DOE, 1983, Future of Electric Power in America: Economic Supply for Economic Growth (June) DOE/PE-0045.

Note: For both types of plants, the figure indicates that the cost per kW increases in real terms as more plants are ordered.

Now, the more plants are built, whether coal or nuclear, the more air pollution (or other perceived hazard) is created, and the more political pressure will be put on the regulatory process to make each plant cleaner or safer in order that the perceived hazard from the larger total population of plants does not increase. Also, the more plants that are built, the more likely it is something will go wrong with one of them and that it will be near populations when it does, causing the communities to take notice. This intensifies popular interest in the subject and, one would expect, increases regulatory pressure to tighten safety or air-pollution standards. Meanwhile, returns on plant investment in cleanliness or safety tend to diminish. You would therefore expect the real cost of each plant to rise geometrically with the numbers of plants built. That is precisely what we observe. In fact, we observe it with a goodness of fit of 93 percent for the nuclear plants and 68 percent for the coal plants. This is a much better fit than any other explanation can command. This does not mean that the explanation is right - correlation never proves causality - but what it does suggest is there is a burden of proof on people who have some other interpretation to show that their alternative fits the data at least as well.

If the Bupp-Derian-Komanoff-Taylor interpretation is correct, it is not very good news for nuclear power. Reducing the disparity in slope between the coal and nuclear supply curves (nuclear being much steeper) appears unlikely. Why? Because in the case of coal, the perceived hazard we are trying to abate (with investment in scrubbers and so on) is very tangible: one can see it, smell it, and wipe it off the windowsill. But in the nuclear case, the hazard is ineffably abstract. While engineers may succeed in reducing the calculated risk of a meltdown from 10^{-x} to 10^{-y} per reactor-year, popular concern is unlikely to be allayed; such alleged reductions in a supposedly unlikely but catastrophic risk have no political meaning. People tend to be much more interested in the large consequence than in the small probability and, therefore, cannot be expected to lower their concerns. Thus, society in the future will likely require bounded additional investments to abate coal hazards but open-ended ones to abate nuclear hazards. It is intriguing, too, that if supply curves are prepared using data from the past two years for such disparate countries as Canada, Britain, France, Germany and the Soviet Union, they will be strikingly similar to the U.S. ones (Harding, 1985). In all of those countries, even the centrally planned economies like France and the Soviet Union, there is now very rapid real cost escalation, apparently for quite similar reasons.

Another way in which we have managed to conceal economic reality from ourselves is through generous subsidies, which are particularly heavy for nuclear plant construction. Roughly 42 percent of the marginal cost of nuclear construction is socialized through tax preferences and another 28 percent or so is deferred to future ratepayers - a total distortion of approximately 70 percent. Thus, while the average delivered marginal price is about 20 cents per delivered kilowatt-hour in 1984 dollars, power can be sold at an apparent price of 6 cents/kWh. If it *looks* that cheap (if we do not know what it really costs) then of course we do not know how much is enough, and we underinvest in energy productivity. Subsidies have led utilities down the path to ruin by encouraging and enabling them to build more power plants - perhaps $100-200 billion worth more - than they will be able to amortize from revenues. The Reagan administration has substantially *increased* such subsidies by every means from illegal enrichment discounts to 10-year nuclear depreciation, Shoreham and TMI bailout legislation, utility dividend reinvestment deductions, and Internal Revenue Service (IRS) permission to finance many nuclear construction costs with tax-exempt pollution-control bonds (because the radioactivity would be a pollutant if released).

The technological history of U.S. nuclear power, like its economic history, suggests a systematic effort to avoid reality. There are a great many conceivable types of reactors: Theodore Taylor has estimated at least on the order of 10^{12} (1984). This number is probably larger when all the possible combination of fuels, moderators, neutron spectra, and coolants are considered. The choice in this country, however, was narrowed very rapidly, mainly under the exigencies of military design. Water cooling began with a decision to locate plutonium production reactors on the Columbia River. U.S. reliance on light-water reactors is largely an outgrowth of decisions concerning nuclear applications to run aircraft carriers. The aircraft-carrier design was put on land and made into a power reactor. The sodium-cooled reactors evolved from their use to power early nuclear submarines. These were not quite as successful, but the technology was still tried on land in what we now call liquid-metal fast breeders.

It is remarkable how a very conservative industry accepted a wild extrapolation of plant size in just a few years: from plants that people had experience with, typically in the 100 or 200 MWe range, to plants in the 800 to 1200 MWe range, which were ordered in very large numbers before such a thing had ever existed anywhere. That is one of the reasons that the whole process came unstuck: at that scale, complexity and new problems arose which were wholly underestimated. Technologists who had previously required themselves to be able to say "We have solved the problem" or "We know how to solve the problem" became intellectually sloppier, content to settle for "We think we will find a way to solve the problem" or, worse, "We know enough to form a judgment that we have a good basis for feeling competent that we will be able to solve the problem." All too often, they did not turn out to know that much, and the cause of problems turned out to be prior solutions.

Safety regulation, in my view, has never been a significant constraint on reactor choice or deployment in this country, simply because the economic pressures on the regulators and their political composition were such that ways were practically always found to issue the licenses. Whenever a problem was discovered which applied to more than one reactor, it would be ruled out of order in the licensing proceedings for any particular reactor, or it would be labelled a "generic issue" and then put aside to be addressed some other time. The list of unresolved generic issues has grown steadily for years. The result has been that when the NRC attempts to resolve one of those problems, it becomes necessary to require retrofits of existing plants and redesign of plants already under construction. This is richly productive of delays and cost overruns. The industry's complaints about the "ratcheting" and "instability" in the regulatory process miss the point. That instability derives from premature deployment of a technology that is not yet ripe. If it were mature - if there were no surprises left - regulation could be stable.

Fuel Cycles

It is important to look at the technological imperatives that drove U.S. fuel-cycle development, because the assumption all along was that it would be essential to move from burner to breeder reactors. This, of course, meant a transition from a uranium to a plutonium economy and therefore to a closed fuel cycle which would reprocess the spent fuel and extract the plutonium for reuse. Hence the only kind of waste management to be considered would be that which dealt with the products of reprocessing - a very complex process which chops up the fuel, dissolves it in acid, chemically recovers the plutonium and unburned uranium, and then isolates the high-level waste from the medium- and low-level wastes and the solid wastes from the liquids and from the gases. This logic, which shaped U.S. strategies for fuel and waste management, unravelled during the 1970s.

First, it was discovered to be hopelessly uneconomic to recycle plutonium in ordinary thermal reactors. Second, the need for the holy grail that drove this whole business, namely, the fast breeder reactor, became subject to searching questions that could not be satisfactorily answered - and not only on grounds of safety and proliferation (Lovins, 1974). As early as 1972, it was pointed out that, according to the official numbers, the price of nuclear electricity would be very insensitive to the price of uranium, and therefore you could afford to search all over for uranium and mine it at a much higher price without making much economic difference (Lovins, 1980a: 70). Cochran also pointed out in a series of cogent studies starting in 1972 that breeders would have such a high capital cost that it would at least offset their proposed saving on fuel, so that the economic need for fast breeders would be pushed at least a century into the future, if not more (see, e.g., 1974). A series of studies by Brian Chow (1979 and 1980) nailed down this conclusion permanently.

Additional arguments were presented. It was noticed in the mid-1970s that the roughly 50-fold improvement in uranium utilization which in principle might be provided by fast breeders would take one or two centuries to achieve, because it would take that long for the fuel cycle to come to equilibrium. In round numbers, it takes about seven tons of plutonium to start up a 1,000 MWe breeder reactor, just to provide its initial core and the pipeline inventory. But running a light-water reactor produces only about a quarter of a ton of plutonium per year. Thus, thirty or so reactor-years of operating conventional reactors are needed to provide sufficient plutonium to fuel *one* breeder. Moreover, the breeders built to date have all been sterile, in the sense that they have not reproduced their initial fuel load fast enough to double it during their lifetimes. Given the thirty or so reactor-years of operation needed to produce the plutonium for one breeder, it appears that if uranium is going to be as scarce as breeder advocates were saying, then it is already too late for the breeder, because so much uranium is needed to run the thermal reactors to fuel the breeders.

During the next eighty years, the uranium saved with breeders (which is only a several-fold saving) could be achieved much more cheaply and surely with uranium-efficient thermal reactors. With present light-water reactors, 15 percent of the uranium could be saved with retrofits; 30 percent in new light-water reactors; and about 40 percent in existing CANDU reactors with low enrichment (Feiveson et al., 1979). If the government insisted upon recycling uranium, but threw away plutonium, nearly 80 percent of presently used uranium could be saved (Feiveson et al., 1979). The added duration of uranium resources would actually be much higher, because these options not only stretch finite uranium supplies, but also make nuclear power less sensitive to uranium prices. If the supply of uranium increases only linearly with price, a 40 percent improvement in the efficiency of using uranium is equivalent to nearly a trebling of the electricity manufacturable at a given uranium price per kilowatt-hour. Thus the 80 percent recovery of uranium possible with non-plutonium, non-breeder fuel cycles using presently commercial reactors can stretch uranium supplies more than twenty-fold.

If uranium scarcity were still a political concern even after reactor efficiency were improved, the long-touted storage advantage of uranium over oil could be cited in support of nuclear burner reactors. With a ten-year stockpile of low-enriched uranium and with uranium oxide (U_3O_8) at $40 per pound, carrying charges on that stockpile would increase delivered electricity prices by less than one percent with the least uranium-efficient reactors known, or by something like one-quarter or one-fifth of one percent with the most uranium-efficient reactors. The sort of uranium stockpiling which Japan has been doing for a long time would be more rational economically than breeders, *assuming* the problem is a potential disruption of uranium supply. Of course, even neglecting all of these arguments, whatever energy security one might gain some time after the year 2100 from fast breeders would only address baseload electricity, which is only about 4 percent of U.S. delivered energy needs. Such "security" would be purchased with the added energy vulnerability inherent in central-electric systems and especially in plutonium fuel cycles, where a breakdown in one reprocessing or fuel-fabrication plant could idle about forty or fifty large reactors at a stroke. These arguments were expressed cogently during the 1970s, especially by the Princeton group (Feiveson et al., 1979). Ignorance is no longer an available defense for nuclear policymakers. They did not, however, acknowledge *any* of these breeder-economics arguments; they were simply overtaken first by the wider collapse of nuclear economics and indeed of central-power-station economics generally.

Meanwhile, practicality also intervened: European experience was showing that reprocessing is a great deal more expensive and troublesome than had been thought (Patterson, 1985). The flagship French plant at Cap La Hague has processed approximately one-tenth of what its builders projected, and is having increasingly serious operational and safety problems. (Some of these are caused by insoluble granules of refractory metals, which, interestingly, would be at least an order of magnitude more plentiful in plutonium fuel than in the uranium fuel reprocessed so far.) No country in the world has made a reprocessing plant work on a commercial basis, and the contract price for reprocessing in France and Britain has increased dramatically; the French price recently increased by a factor of seventeen in nominal francs over ten years. The doubling time of the real cost increase has at times been less than a year and may be getting shorter. In fact, French and British reprocessing contracts reportedly contain a clause allowing the contractor, for any reason or none, to not reprocess, return the fuel to the customer in whatever condition it happens to be in, and keep the customer's money - hardly an indication of confidence in the technology.

Reprocessing also turns out to make waste management a great deal more difficult. It results in thirty to fifty times the initial volume of waste materials which have to be looked after for a very long time. Furthermore, reprocessing produces a diversity of wasteforms. Some of the wastes have high thermal power density; some are gases, including labile gases like tritium; some are corrosive; and some have enormous surface area (all of the old paper towels, rubber gloves, and bits of plumbing that are called "low-level transuranic" waste). Taking these factors into consideration, reprocessing appears to make the waste management problem more intractable than simply packaging spent fuel and storing it - although we have yet to determine where that might be (Patterson, 1985; Hatzfeldt, 1979).

There is no question that the waste can be stored safely in the ground; the concern has always been how long it will stay there. Yet the Department of Energy has returned to the position held by the AEC in the early 1970s, asserting without a storage plan and site in place that the waste problem is solved. DOE's "policy" is that we will reprocess, as if anybody were there to do it. Supposedly, the high-level waste will be converted into borosilicate glass and buried in salt. Yet it has been known for seven or eight years that borosilicate glass and salt is the *least* compatible known combination of wasteform and host rock. When the glass is put in salt, the water in the salt migrates toward the heat and makes brine. Hot brine rapidly dissolves virtually anything (except gold). In fact, it decomposes borosilicate glass in a matter of weeks.

We have come full circle to where we were over a decade ago in understanding the waste management problem, yet we still have essentially no respectable technical base for it that does not run through the reprocessing route. All that we have to show for the effort is a scientifically designed white elephant. The breeder reactor accumulated the largest R&D expenditure on a single project in U.S. energy history, but its proponents failed to address the right problems.

Technology Is The Answer!
(But What Was The Question?)

With the demise of the Clinch River project in 1984, we now see more clearly the rapid emergence of nuclear fusion as the second-biggest money-gobbler in the federal civilian energy budget ($440 million in the FY 1985 appropriation). The fusion program has become in part a welfare program for unemployed fission technologists. If they are successful in developing the technology (which will be much tougher than putting people on the moon) and if waste, safety and safeguards problems can be made tractable (which is by no means assured), fusion will then be an even more clever way than fission to do something we do not need to do - manufacturing more big blocks of expensive electricity for which there will not be a market. For that reason, fusion will not be economically sound and, therefore, little point exists in arguing about its safety, environmental value, or beauty. We just should not support the program with public money.

The shift in emphasis from breeder to fusion technology - along with some rather expensive wishful thinking DOE is encouraging about "next-generation" fission reactors, as if there were going to be any - recalls Santayana's remark that "fanaticism consists in redoubling your efforts when you have forgotten your aim." I think that is exactly what the technological history shows in the case of nuclear power: repeated efforts to invent a better horse and buggy. Yet technological history is only the most superficial layer of what went wrong. More profoundly, the federal energy establishment fundamentally misunderstood its mission. It perceived (and still perceives) its mission as the development of a new piece of hardware, a kind of magic bullet, in which the economics would take care of themselves. The rationale seems to be that as long as the technology is sufficiently sweet (meaning that it delivers large chunks of electricity from something ingenious and complicated which employs many high technologists for decades or, preferably, millenia), the hardware magically would be delivered, used, and preferred. This manner of thinking fundamentally mistakes what the energy problem is, and what the federal role should be in addressing it.

American society and its economy do not require electricity for its own sake. Raw kilowatt-hours are useful to nobody but executioners. There are uses of energy for which electricity is the only or the best form, and there is no question that electricity is a very high-quality form of energy. Our problem, however, is not a shortage of electrical generating capacity. If all power plants already built in the U.S. could sell all of their output when operated at capacity, approximately 16 percent of delivered energy in the U.S. would then be in the form of electricity. Currently, only 13 percent of delivered energy is electrical, the other 3 percent representing idle generating capacity. Electricity is very expensive, with the national average price for all sectors nearly 7 cents per kilowatt-hour - the equivalent, in terms of heat content, to oil at about $120 per barrel. Therefore, the uses for which electricity is economically worthwhile are limited to special ones like motors, lights, smelters, and so on. Electricity is fundamentally uneconomical in thermal markets (58 percent of our delivered energy needs) and in road vehicles (about 34 percent of our needs). Only about 8 percent of our delivered energy needs can be economically met by electricity even at present (very low) levels of end-use efficiency. Thus, the U.S. *already* has roughly twice the electrical generating capacity that it needs.

In this respect, the market for electricity is and has been oversupplied. Yet, electricity has historically taken on the order of three-quarters of the energy R&D budget - never less than 60 percent. In the 1984 budget request from DOE, for example, the civilian energy budget (of which roughly one-third was for basic research and two-thirds was for hardware) dedicated over half to nuclear-related electricity projects alone. Of the entire civilian energy budget, 65 percent was nuclear - not counting some things on the nuclear side that are military (like laser fusion). Of all the hardware research, 92 percent was for electricity. Of all the energy supply dollars, 96 percent was for electricity (DOE, 1983a). Of all the electric dollars, over 99 percent was nuclear. All of that funding for 8 percent of the problem!

Electricity will not be made more competitive by increasing plant generating capacity. But just such an assumption is embodied in federal electricity R&D budgets. There are more than 50 kinds of diseconomies of scale which have to be taken into account along with the several economies of scale, because what we are interested in is *net* economics, not gross (Lovins and Lovins, 1982: Appendix A). It has already been carefully shown that - except in very unusual cases like running a smelter - it is much cheaper to build small power plants than large ones (Lovins and Lovins, 1982: Appendix A). It would be also far less risky for the utility. The Edison Electric Institute now admits this reality and favors only small, fast, cheap investments (Bauer, 1984).

Will we need more electricity in the next decades? There are light bulbs now available with four times the efficiency of the standard bulb. These bulbs render obsolete about 25,000 MWe of power plants - $60 billion worth at today's marginal prices. There also are high-frequency ballasts, paying back their cost in about a year, that can be installed in overhead fluorescent lights. Those render obsolete about another 60,000 MWe. Energy-efficient refrigerators remove the need for 20,000 to 25,000 MWe. Alone, these refrigerators displace roughly one-half of the nuclear capacity today. In fact, *all* U.S. nuclear capacity could be replaced just with proper sizing, coupling and controlling of industrial electric motors, saving about 70,000 MWe installed at a cost of under one cent per kilowatt-hour (Lovins, 1985a and b).

If full use were made of the best electricity-saving devices now available, that would at least quadruple the efficiency of using electricity in this country, at a cost of less than two cents per kilowatt hour in 1984 dollars (Lovins, 1985a and b). That is less than just the *running* cost of any thermal power plant, including a nuclear one. As a consequence, once Seabrook I or Palo Verde or Diablo (or any other nuclear plant in the construction pipeline) is completed, it will be cheaper to write it off and buy efficiency than to operate it (Lovins, 1984 and 1985a and b). Between 80 and 90 percent of the electricity now sold in this country is or will shortly be uncompetitive with the efficiency improvements now on the market. Nonetheless, we continue to devote nearly all of the federal R&D budget to developing more ways to make expensive electricity - more ways to make the unsellable. In the case of power plant R&D, it means the development of the unfinancible to make the unsellable.

The Department of Energy persists in forecasting high electricity demand - so high, indeed, that about two-thirds of all primary energy growth to the year 2000 is officially projected to go to conversion and distribution losses (mainly cooling-tower plumes and warm condenser water) and never to get to the consumer at all! Indeed, a 1983 DOE report argued that to keep the lights on in the 1990s will require utilities to order another trillion 1982 dollars' worth of power plants over the next couple of decades (DOE, 1983b). That amounts to ordering big power plants at a rate averaging one a week, in a country that has ordered only a handful of smallish coal plants since late 1981. The Fourth National Energy Policy Plan declared that it saw little or no workable competition for electricity (discussed in Lovins and Lovins, 1984). That is not much further on than we were in 1972, when the AEC was unable to cite a single literature reference on the possibility of saving energy (JCAE, 1972b: E1109). A detailed government report called *A New Prosperity,* produced by the Solar Energy Research Institute in 1981, is apparently on DOE's index of prohibited reading (see discussion in Lovins and Lovins, 1984). It is not even mentioned in DOE's forecasting documents, even though it is the best end-use/least-cost analysis that has been done in this country. The evangelical theology which holds that electric use and GNP must spiral ever upwards in a frenetic embrace continues to dominate our energy policy. It comes in part out of the Office of Policy, Planning and Analysis at DOE, a name which I think correctly reflects its priorities: policy first, analysis afterwards.

The Department of Energy and its predecessors have assumed that all that is needed is to develop the right kind of power plant, and the utilities will buy it and get the electricity out there. Having failed to resist the department's strategy, the average utility now is bankrupt in all but name. It spent the 1970s increasing its construction expenditures eight times as fast as its cash earnings, and borrowing about two-fifths of its dividend payments. In effect, this industry has gone broke, liquidating itself to build power plants that it does not need, cannot afford, and will not be able to pay for. It has been playing "You Bet Your Company" that it will take customers 50 years to discover better buys. It is not taking customers nearly that long.

Utilities are competing in a highly competitive energy-service marketplace. They have to compete with weatherstripping, with motor controls, with better ballasts and lights. If they fail to do so, they will simply find (as they already have begun to) that higher prices *reduce* their long-run revenues. Their product is already so uncompetitive that pricing it higher loses market share.

There are some very exciting things utilities can do (as a few are doing) to participate financially in efficiency improvements so that the industry again can become a declining-cost industry and so that firms once more have reasonable cashflows (Lovins, 1985a and b). The Department of Energy is not in the least interested in that sort of survival strategy. But the economics which DOE has long ignored actually are paramount. Since 1979, this country has gotten *over one hundred times* as much new energy from savings as from all net expansions of supply combined (Lovins, 1985a and b). More new energy has been developed from renewable sources than all of the non-renewables. More new generating capacity has been ordered from small hydro and windpower than from coal or nuclear plants or both, without even counting cancellations (Lovins, 1985a and b).

If you want to gauge where the market is headed, consider California, where since 1981 the utilities have been offering to buy privately generated, privately financed power for a little less than it would cost them to make it themselves. At the end of 1984, some 20,300 MWe of privately generated power had been firmly offered, over half of it from renewables (Lovins, 1985a and b). The principal supply sources were industrial cogeneration (some of it biofueled), wind (4,000-plus MWe), small hydro, and geothermal. But there is every other source in there also, from photovoltaics to generating energy from burning peach pits (or energy studies). The proffered supply at less than full avoided cost has lately been increasing at the rate of nine huge plant-equivalents per year. It is coming in so fast the California utilities do not know what to do with it; and the sudden glut, with enough small-power production already on offer to displace three-fourths of the state's entire peak output from nonrenewable sources, forced the suspension of small-power contracting in April 1985. Yet, two dozen states and provinces still hope to sell California *their* surplus power, all simultaneously.

Nonetheless, DOE steadfastly ignores economic reality, continuing to subsidize nuclear power heavily. Preliminary results of a comprehensive analysis of federal energy subsidies, being conducted by Heede (1985) at Rocky Mountain Institute, suggest how misguided national policy has been. Heede estimates the subsidy *just in* FY 1984 (major programs only) to be *$46 billion,* of which civilian nuclear fission received $15.8 billion. In terms of million Btu supplied per 1984 dollar of subsidy, nuclear power subsidies are calculated to have "produced" 0.07 per dollar, compared to 0.4 for hydroelectric, 1.7 for other renewables, 2.4 for oil, 3.8 for natural gas, 5.8 for coal and 13 to 26 for end-use efficiency. Thus in 1984 a dollar spent on subsidies to efficiency and renewables yielded about 80 times as much energy as a dollar spent on nuclear power. Per unit of energy, counting electricity at its heat value, electricity was 11 times as heavily subsidized as direct fuels, and at least 48 times as heavily subsidized as end-use efficiency.

Mistaken Mission

The fatal error made by DOE regarding nuclear power was supposing that the problem was hardward, not social. The public has perversely refused to evaluate and accept nuclear power as the department's analysts thought they would (or should). This has been variously ascribed to ignorance or hysteria (and indeed DOE hired a psychiatrist in 1984 to access the public's irrational "nuclear phobia"). We have also found *within* the nuclear business that the paramount problems are those of people, not of engineering. In fact, some of us are particularly concerned about the declining quality of the people going into that business: it is passing, as Nobel physicist Hannes Alfvén told the 1980 Geneva IAEA conference, "into ever less competent hands." Probably the best half of the people in the industry have already departed. It will become even harder in the future to get talented people to devote their careers to looking after the garbage; it is just not a very interesting thing to do. A dollar invested now in solving the unsolved problems will buy less solution than it did in the days of the pioneers.

DOE has never compared hardware options symmetrically with policy actions - for example, accelerated scrappage of cars or better information programs on efficient appliances versus developing some new kind of gadget with brass knobs all over it. Nor has the Department ever symmetrically compared supply expansions with energy-productivity improvements, least of all in cost.

It is difficult to find a major public-policy decision about energy in this country that was based on economics. The decisions have instead been based on political expedience, and then the economics were made to come out to justify what was done (usually by juggling subsidies). In that mode, federal energy policy is increasingly irrelevant, and will continue to be so until it addresses what is happening in the marketplace and why. The Department of Energy and its predecessors have never put down on one piece of paper the marginal cost of providing a given energy service from a variety of measures so that it is possible to compare them. This is absurd and a cause for national shame.

The Department of Energy has never considered the political impacts of its policies, although those are no less real than any other kinds of impacts. Neglecting them has resulted in many DOE-developed technologies' coming unstuck. A whole constellation of concerns has been ignored. How are the risks and impacts of the technology perceived? Are they relatively understandable? directly sensible? Are they susceptible to commonsense judgments by generalists? Is the proposed technology or action potentially vernacular, accessible to many actors (and many levels of sophistication or complexity), or is it just the exclusive realm of a technological priesthood? In political terms, is the technology centrist or centrifugal, autarchic or localist, implemented by fiat or by market choice, technocratic or accountable, loose-fitting or unforgiving, comprehensible or arcane? How does it affect federal versus state or local roles, settlement patterns, big versus small business, homogenization versus pluralism, rural versus urban, distributional equity, interregional and intergenerational equity? Does it allocate the social costs of energy essentially to the same people at the same time, or to different groups at different places and times? These are really key questions for policy. They've never been *asked* in DOE, let alone answered.

In short, I think the Department of Energy and its predecessors came unstuck by never asking the basic questions:

- What do we want the energy for?
- What is the amount, type and source of energy that will do each task in the cheapest way - cheapest in the broadest sense?
- What actions are required? Are they hardware or policy actions?

Once you have answered these questions, *then* you can start to figure out what the federal government needs to do. In fact, the Department of Energy has taken very nearly the opposite approach. DOE *starts* with existing or hoped-for bits of R&D which reflect contractors' and technologists' "wish lists" - what they would most like to play with. Then DOE tries to find a use for those bits of hardware. And, lastly, belatedly, often unsuccessfully, it tries to figure out how to make the marketplace absorb the hardware. As Herman Daly once remarked, that procedure "is unworthy of any creature with a central nervous system, let alone a cerebral cortex. And for those of us who have souls," he added, "it is incomprehensible in its inversion of means and ends."

This is the first time in many years that I have written on nuclear issues (other than proliferation). I try to avoid the subject for three reasons. First, it is so dead that its only value is as a cadaver for policy autopsy, and I would not want to be thought so dull as to be spending a lot of time kicking a dead brontosaurus. Second, it always saddens me to think of the lives, careers, money, and other resources that this national tragedy has consumed. Third, thinking about that tragedy makes me feel that there but for the grace of God go I. For in my student days I received national awards for nuclear-physics research from, among others, Westinghouse, General Electric, the AEC (Glenn Seaborg was the judge), and the American Nuclear

Society. My local utility sent me to the National Youth Conference on the Atom. When all I knew about nuclear power was what its promoters told me - which I uncritically accepted until nearly 1970 - I thought it sounded like a great idea. I doubt those promoters knew better themselves: they simply repeated what their peers all said and what they so desperately wanted to be true.

In that spirit of sad respect for the ordinary human frailities which produced the nuclear fiasco with such Sophocleic inevitability, I would like to close with an epitaph which I wrote some years ago for the nuclear industry:

> When the history of the nuclear controversy comes to be written, those who killed nuclear technology will be seen to have been its most avid promoters, who systematically mistook hopes for facts, advocacy for analysis, commercial zeal for national interest, expertise for infallibility, engineering for politics, public relations for truth, and the people for fools.

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U.S. Nuclear Exotica:
Peaceful Use of Nuclear Explosives

Richard T. Sylves

Project Plowshare, the U.S. Atomic Energy Commission (AEC) program to investigate possible non-military uses for nuclear explosives, was an offshoot of President Eisenhower's "Atoms for Peace" proposal. In a speech delivered December 8, 1953, Eisenhower declared, "this greatest of destructive forces can be developed into a great boon for the benefit of all mankind" (Hilgartner, et al., 1983: 41). After World War II and through the 1950s, many scientists, engineers, and government officials shared a vision of a nuclear utopia. Nuclear power was expected to propel aircraft, trains, naval vessels, commercial ships, rockets, and even military vehicles (Hewlett and Duncan, 1969; Hilgartner, et al., 1983; AEC, 1963: 10). Many also believed that atomic energy would be used to genetically alter crops and preserve grains, meat and fish. Moreover, nuclear reactors were envisioned which would generate huge quantities of cheap electricity (Hilgartner, et al., 1983: 43).

This scientific fascination with potential applications of atomic energy spawned a wide variety of military and civilian AEC research and development contracts, some of which were successful and many of which were not. For many advocates of nuclear technology, mechanical applications were not enough. There were those who believed that the power yielded by the thermonuclear bomb itself could have peaceful applications. Nuclear swords were to be transformed into plowshares that would dig new harbors and canals, cut gorges through mountain ridges, and open valuable mineral deposits (Hilgartner, et al., 1983: 43).

The idea for Plowshare originated at the Livermore Laboratory of the University of California in 1956. A classified symposium on peaceful use of nuclear explosives was held in February 1957 at the