NUCLEAR POWER AND THE LARGE ENVIRONMENT

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Abstract

Following the discovery of radioactivity, and well before the discovery of fission, it was recognized that atoms "contain enormous stores of energy," with the potential for major military and peaceful applications. The peaceful applications bore fruit in the 1950s and1960s, with the first electricity from nuclear reactors. but after a period of optimistic expansion the rate of development was slowed by economic problems and environmental concerns. While in recent years nuclear power has providedabout 20% of U.S. electricity and about 17% of world electricity. environmental concerns have led to a de facto moratorium on new reactors in the United States and in much of Europe. Some of these concerns have focused on situations involving small estimated radiation exposures (e.g., the Three-Mile Island accident and the proposed Yucca Mountain repository) and some on events involving appreciable exposures (e.g., Chernobyl). However, whatever attention they may deserve, these sources of concern are dwarfed in importance by possible impacts of nuclear power on the large environment: (a) the coupling between nuclear power and nuclear war, (b) the extent to which nuclear power could mitigate global climate change, and (c) the relationship between energy supply and the world's ability to sustain a large population. Consideration of these impacts should be central to nuclear energy policy.

1. Introduction

The development of nuclear energy has come to a near halt in the United States and in much of the rest of the world. The first era of reactor construction in the United States ended in 19% when the last reactor in the pipeline was put into operation. The current hiatus, although unfortunate from the standpoint of the orderly development of the technology, provides an opportunity to step back and take a long-range view of the past and possible future roles of nuclear energy.

The most serious obstacle to nuclear power today in many countries is the strength of public opposition. The objections that have resonated particularly strongly with the public stem from fears of nuclear radiation. In addition, a dislike of the institutions surrounding nuclear power played a part in the original opposition. The federal government and the nuclear industry were seen as mingling their promotion of nuclear power and nuclear weapons, and doing this in an arrogant fashion, insensitive to public concerns.

These institutional objections may have faded somewhat with time, and in now considering nuclear power---with its potential for major positive and negative impacts---it is valuable to establish afresh the relative importance of the considerations that enter into the evaluation. Omitting intrinsically minor matters that have been more distracting than substantive, there are at least five areas of major concern: ***nuclear reactor safety, nuclear waste disposal, nuclear weapons proliferation, global climate change,*** and ***energy scarcity in a world with a growing population.*** The intent of this paper is to show that these issues can be placed into two differing categories, on the basis of the scale of risks involved:

- Confined risks. These are risks that can be quantitatively analyzed, and for which both the likelihood and the scale of possible damage can be made small, given prudent caution.

- Open-ended risks. These are risks that cannot be well quantified by present analyses, but which involve major dangers on a global scale.

In subsequent sections of this paper, it will be argued that the risks that are most in the public consciousness---those associated with reactor safety and nuclear waste disposal---are in the confined category, while the remaining three problems are in the more threatening, open-ended category and therefore should be the major factors in determining energy policy, including policy towards nuclear energy.

2. **Historical background**

The history of nuclear energy goes back to the early days of radioactivity studies, when awareness developed of a new, previously unsuspected, source of energy. Thus, in 1911, writing for the 11 th Edition of the Encyclopedia Britannica, Ernest Rutherford called attention to the large energies released in radioactive decay and interpreted that as meaning that "atoms contain enormous stores of energy." In 1913 the British novelist H.G. Wells predicted the use of atomic energy for industrial and military purposes. The first glimpse of a way to extract this energy came with speculations by Leo Szilard, shortly after the discovery of the neutron in 1932, about the possibilities of a nuclear chain reaction. The chain reaction---based on processes quite different from those originally contemplated by Szilard---was achieved by Fermi and his team in 1942. With what now seems breakneck speed, a 250 MWt reactor was built at the Hanford reservation in Washington and put into operation in 1944 for the production of plutonium. The atomic bombs followed in 1945.'

The first realization in the U.S. of the potential of nuclear energy for generating electricity came with the completion of the Shippingport reactor in 1957, but the large scale deployment of nuclear power did not begin until the late 1960s. A flood of reactor orders began in 1965 and continued into the mid-1970s, but every reactor ordered after 1973 has been cancelled (Figure 1). Thus, almost all reactors in operation today were ordered in the nine-year period from 1965 through 1973.

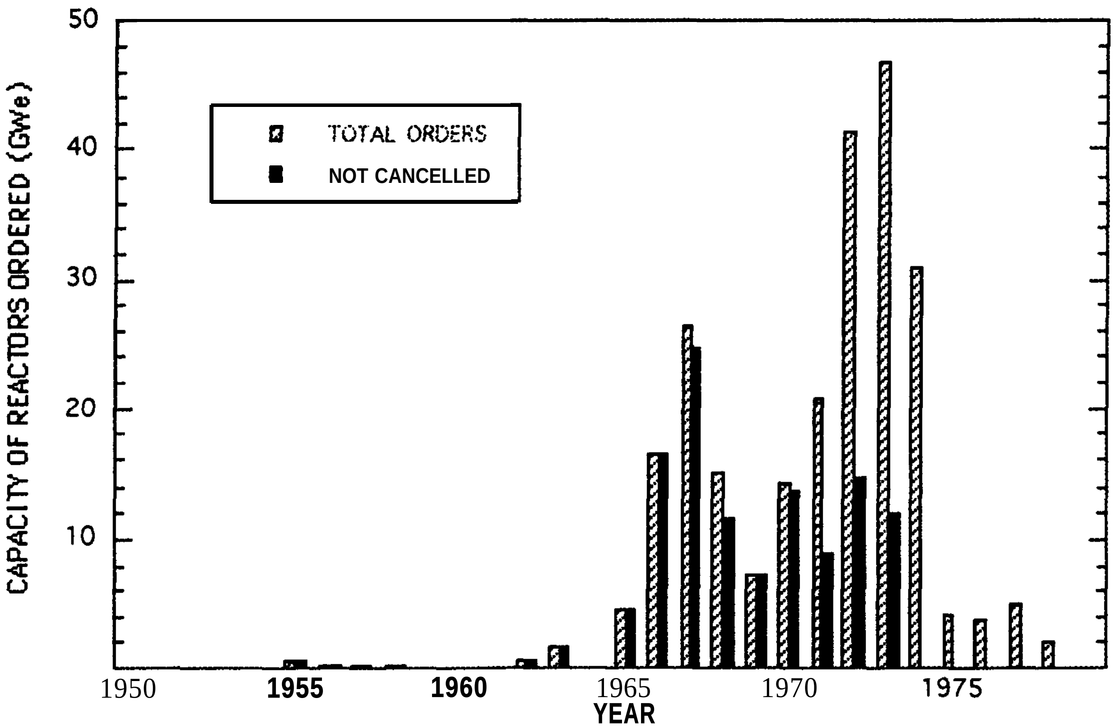

FIGURE 1. Reactor orders in the United States, 1953 – 1978, in Gwe of total capacity. Annual figures

are given for total orders and for those that were not subsequently cancelled. [Copied from Ref. 1, p.11.]

The subsequent rapid reversal of fortunes for U.S. nuclear power was due to a complex of factors, including:

- A sharp drop in the rate of growth of electricity demand, from an average of 7.5% per year in the decade from 1963-1973 to an average of 2.6% per year in the next two decades.

- Unexpected increases in the cost of constructing and operating nuclear plants, without a corresponding rise in the costs of electricity from coal-fired plants.

- Difficulties in achieving uninterrupted reactor operation, probably stemming in part from the compressed pace of the initial expansion and also contributed to by retrofits designed to improve reactor safety.

- Vigorous opposition to nuclear power, coupled with a regulatory and legal system that made it relatively easy for opponents to slow, or even prevent, the completion of reactors.

Electricity generation today is dominated by fossil fuels, primarily coal, which together provided 69% of the electricity generated in the United States in 1997. Nuclear power produced 18% (20% if electricity from non-utility producers is excluded). Another 12% is was provided by renewable sources, including 10% from hydroelectric power, 1.7% from wood and waste, 0.5% from geothermal, 0.10% from wind, and 0.03 % from photoelectric and direct thermal sources.

It is striking that the renewable sources which produce the most electricity---hydroelectric and biomass---are not readily expandable, while the sources that have the most opened-ended potential in terms of the size of the available resource---wind, photoelectric, and thermal---produce so little that it is difficult to assess the practicality of an eventual large-scale expansion.

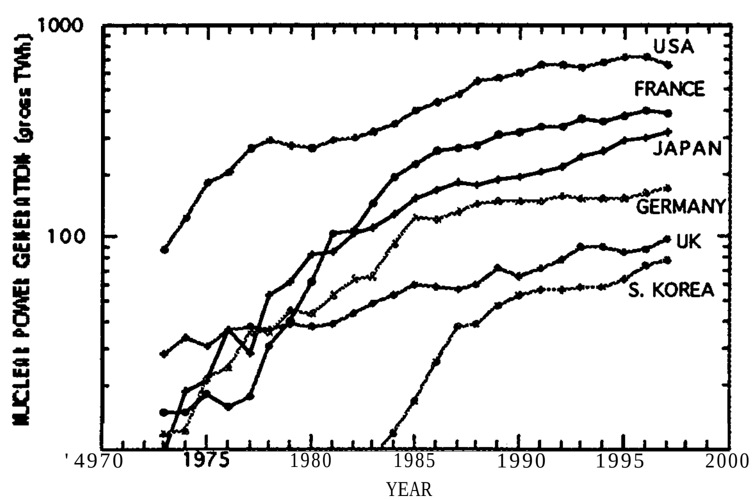

FIGURE 2. Nuclear power generation in selected countries, 1973-1997.

Nuclear power still provides almost 20% of U.S. electricity, with 104 operating reactors, but this is a much smaller share than anticipated several decades ago and is likely to shrink as some existing plants are shut down. There are no new reactors under construction in either the United States or Western Europe, but there are continuing building programs in some other countries, particularly in Asia where Japan and South Korea remain committed to nuclear power development. France now obtains over 75% of its electricity from nuclear power, but has no need for additional plants in the immediate future. Nuclear power generation in the United States and several other leading nuclear countries is plotted in Figure 2, for the period from 1973 to 1997.

3. **Confined dangers.**

a. Nuclear reactor accidents.

The belief that reactor accident risks are small is based on detailed analyses of reactor design and performance. It is supported by the very good past safety record of nuclear reactors, excluding the accident at Chernobyl in 1986. The defects in the design and the operation of the Chernobyl reactor were so egregious that the Chernobyl experience holds few lessons for the nuclear industry outside the former Soviet Union---except to serve as a reminder of the vital importance of establishing and maintaining meticulous, safety-conscious practices in the design, construction, and operation of nuclear power plants.

Excluding reactors in the former Soviet Union, at the end of 1998 there had been over 8000 reactor-years of operation in the world, including about 2350 in the United States.[3] There has been only one major accident---the Three Mile Island accident---to mar an otherwise excellent safety record for these reactors. Even at TMI, although the reactor core was severely damaged, there was very little release of radioactivity to the environment outside the reactor containment and very little exposure of either workers or the surrounding population.

Subsequently, U.S. reactors have been retrofitted to achieve improved safety and their operation has become steadily more reliable. The Nuclear Regulatory Commission keeps records of the equipment failures which, were other things also to go wrong, could be “precursors” to accidents involving reactor core damage.[4] This record has continually improved over the past two decades. In 1997, for the 100-plus reactors in the United States, there was no precursor event for which the calculated chance of subsequent core damage was as much as one in 10,000. The chance of a major release of activity into the outside environment was not calculated in this analysis, but is still smaller---as indicated by the effectiveness of the reactor containment at Three Mile Island.

A next generation of reactors can be even safer, either through a series of relatively small “evolutionary” steps that build directly upon past experience or through more radical changes that place greater reliance on “passive” safety features---such as cooling water systems that are directly triggered by pressure changes (rather than by electrical signals) and that rely on gravity (not pumps).

b. Nuclear waste disposal.

The second dominant public concern is over nuclear wastes, partly due to the association in the public mind between the spent fuel from nuclear reactors and the various liquid wastes from the nuclear weapons program. Some of the latter have leaked from their containers, but this cannot happen for the civilian wastes because the fuel removed from the reactors is in solid form and will remain solid when placed in its final repository.

The hazards from nuclear waste disposal are low due to the small volume of the wastes, the ruggedness of the containers in which they are scheduled to be put, and the slow movement of water in the ground from a site such as Yucca Mountain to the surface or to potential water sources. Isolation of the wastes from the environment can almost surely be achieved for thousands of years, a time sufficient for most (but certainly not all) of the radionuclides to have decayed to negligible levels.

To evaluate the degree to which the wastes will remain out of the accessible environment, innumerable studies have been made of properties of the waste containers and of the geological site in which they would be placed. One way to form an opinion of the risks is to examine these studies along with the expert independent reviews that are being made of them. It is also possible to gain a perspective on the scale of the problem by considering the protective standards that have been proposed for Yucca Mountain.'

The first of these standards was put forth in preliminary form by the Environmental Protection Agency in the early 1980s. It set limits on the release of radionuclides, designed to satisfy the criterion that the number of fatal cancers be below 1000 (for a repository holding about 100,000 tonnes of spent fuel) for a 10,000-year period---i.e. an average of less than one cancer fatality per decade. This standard appeared not only to be convincingly stringent, but also to be achievable. Even in the event of degradation of some of the protective canisters, the transfer of radionuclides from the repository to the populated environment normally would be retarded by the slow movement of water through the ground and by the even slower movement of most of the radionuclides carried by water.

However, gaseous paths were originally overlooked, and the development of the site was put in jeopardy when it was later recognized that escaping ^{14}C could reach the "accessible environment" relatively quickly in the form of gaseous carbon dioxide. This radionuclide is naturally produced in the atmosphere by cosmic rays and it is familiar as the key to "carbon dating." It contributes about 1 mrem per year to the total dose from natural radiation out of about 300 mrem per year received by the average person in the US. A release over several centuries of the entire ^{14}C inventory at Yucca Mountain would increase the worldwide atmospheric concentration of ^{14}C by only about 0. I%, but it would nonetheless violate the established EPA limit.[6] Thus, the EPA was trapped by the form of its original standards, even if it defied common sense to be concerned about a minuscule increase of a very minor natural pollutant.

It is startling that ^{14}C might have been the show-stopper for Yucca Mountain, but it appeared that this could be the case, until Congress took away from the EPA the authority to set Yucca Mountain standards pending recommendations from a panel to be established by the National Academy of Sciences. This panel issued its Report in 1995.' Among other things, the Report suggested that the ^{14}C problem could reasonably be put aside. But in the end---gauged by its relevance to real concerns---the NAS Report represented little improvement over the earlier efforts by the EPA. It recommended extending the period of concern from 10,000 years to a time up to one million years, and establishing as the key criterion the average risk to members of a "critical group" (probably numbering less than 100), representing the individuals at highest risk from potentially contaminated drinking water. It was recommended that their calculated average risk be limited to 10^{-6} per year or 10^{-5} per year. According to the estimates now used by federal agencies to relate dose to risk, this range corresponds to between 2 mrem/year and 20 mrem/year---at worst, less than 10% of the average natural radiation dose in the United States.

The attempt to extend this high level of protection to 100 people living 500,000 years hence may have stemmed from the difficulty of finding a less demanding standard that did appear indifferent to the welfare of future generations. This was especially hard for a panel that felt constrained to consider future generations to be the same as our own---in lifestyle, technology, and rights. But, whatever the difficulty of finding a more moderate stopping point, this end result appears as almost irrelevant distraction, considering the serious dangers that the world must take into account in developing energy policies. For the EPA to accept these recommendations would in the minds of many observers defy common sense, but for it to depart from them could create a serious political storm. Therefore, it is not surprising that---almost four years after the publication of these recommendations---the EPA has not put forth its own proposed standards.

Those who persist in demanding standards of such rigor, or still more rigorous ones, call to mind an image of a princess who declines to recline on the royal bed unless the chance that there is a pea under the mattress is less than one in a million. Her concern, one may surmise, is not fundamentally with the pea. She just does not like the prince. And so it may be with nuclear waste disposal. In many ways it has become a surrogate issue, which serves as an effective target in a campaign driven by a much broader dislike of nuclear power.'

4. **Open-ended risks**

a. Nuclear weapons proliferation.

The first of the open-ended problems to be considered---involving not minuscule risks to few people in the distant future but grave risks to many people on a time scale of decades or, at the most, centuries---is nuclear weapons proliferation, discussed here in terms of its relation to commercial nuclear power. Despite many differences, there are overlaps in military and civilian nuclear technologies as well as in the institutions and individuals working on each. Looking to the future, a country that has people familiar with using nuclear power to generate electricity and that has some of the necessary equipment has gained a head start if it wishes to pursue a weapons program. This is a live issue at present in the case of Iran, with the United States opposing the Russian efforts to help Iran in its purportedly civilian nuclear program.

However, the potential case of Iran aside, commercial nuclear power has played little role in nuclear weapons proliferation. The long-recognized nuclear weapons states---the United States, the Soviet Union, the United Kingdom, France, and China---each had nuclear weapons before they had electricity from nuclear power. India's weapons program was initially based on plutonium from research reactors and Pakistan's on enriched uranium, although this does not rule out the possibility of later linkages between their weapons and civilian programs. The three other countries that currently have nuclear weapons, or are most suspected of recently attempting to gain them, have no civilian nuclear power whatsoever: Israel, Iraq, and North Korea. Further, many countries started their weapons programs using ^{235}U as the fissile material, not ^{239}Pu as would be the case in the usual proliferation scenarios.[9]

Overall, the links between commercial nuclear power and weapons proliferation have been weak. In any event, having the United States relinquish nuclear power would not help to thwart potential proliferation unless at the same time we would relinquish our own nuclear weapons and could stimulate a broad international taboo against all things nuclear. The so-called "nuclear-free" zones that exist in limited regions of the United States reflect such an aspiration. But at the present time, 32 countries use nuclear power for generating electricity and many more have research or test reactors. A comprehensive nuclear taboo is highly unlikely, given the heavy dependence of France, Japan, and others on nuclear power, the importance of radionuclides in medical procedures, and the wide diffusion of nuclear knowledge among countries that differ greatly in their political systems, their senses of political morality, their economic options, and their perceived military pressures.

A more direct hope---although admittedly not a very secure one---lies in stringent control and monitoring of nuclear programs, such as attempted by the International Atomic Energy Commission. The United States' voice in the design of future reactors and fuel cycles and in the shaping of the regulatory regimes that might govern them is likely to be stronger if the United States remains a player in the civilian nuclear power enterprise. Our offer to help North Korea obtain two commercial reactors in return for ending its nuclear weapons program illustrates the ways that capabilities in civilian nuclear power can be used to further anti-proliferation goals.

Further, the threat of future wars may be diminished if the world is less critically dependent on oil. Competition over oil resources was an important factor in Japan's entry into World War II and in our military response to Iraq's invasion of Kuwait. Nuclear energy can contribute to reducing the urgency of such competition, albeit without eliminating it.

Finally, there is the risk that terrorist groups could steal potential bomb materials. Such concerns influenced the decision in the United States in the late 1970s to abandon the reprocessing of spent fuel." This lead has not been followed elsewhere, with France, India, Japan, Russia, and the United Kingdom continuing their reprocessing programs. This issue may become crucial if nuclear power is to continue operation far into the future and breeder reactors are found to be essential. There is no immediate pressure to move to breeder reactors, because present uranium supplies could accommodate a large nuclear expansion through the next century. Nonetheless, if one takes a long-term view, it is an important technical challenge to find fuels cycles that exploit more of the energy potential of uranium or thorium without increasing the opportunities for the diversion of fuel to bombs.

At present, however, none of the links between nuclear power and nuclear weapons appears to be very strong, and even the net direction of the possible coupling is in doubt. Thus, while the dangers from nuclear weapons involve such major consequences that they must continue to be examined and taken into account, it is not clear whether consideration of these dangers will provide a stronger argument for nuclear power or against it.

***b. Global climate** change.*

The prospect of global climate change arises largely from the increase in the atmospheric concentration of carbon dioxide that is caused by the combustion of fossil fuels. As discussed, for example, in the reports of the Intergovernmental Panel on Climate Change, there is a significant possibility of large, and in balance harmful, effects." The projected temperature increase by the year 2100 is in the range from **1C** to 3.5 C, with a most probable value of 2 C. The projected sea level rise is 15 cm to 95 cm, with a most probable value of 50 cm. These increases would continue beyond the year 2100.

We will not explore the predicted effects further, but note that most governments profess to take them seriously and, more importantly, most atmospheric scientists take them seriously. Under the Kyoto agreements, the United States committed itself to bring carbon dioxide emissions in the year 2010 to a level that is 7% lower than the 1990 level---in effect, given the intervening increases, 15% lower than 1997 level. This is a difficult target to achieve. It is not a particularly meaningful one except for symbolic purposes, but the broad goal of restraining carbon dioxide emissions through the next century remains important. Nuclear power is not the only constructive option towards this end. Renewable sources are also a possibility, but the practicality of **large-**scale development of the most promising forms, namely wind and photovoltaic power, remains to be demonstrated. There is undoubtedly an important further role for conservation, and a somewhat speculative possibility of large-scale carbon sequestration, but if the reduction of carbon dioxide emissions deserves high priority, it is foolhardy for the United States and other countries to ignore the contribution that nuclear power can make.

The example of France clearly demonstrates the potential of nuclear power. France in 1997 obtained about 78% of its electricity from nuclear power and only about 5% from coal. For the United States, in contrast, the comparable numbers were 18% from nuclear and over 50% from coal. The use of coal for electricity generation is responsible for about 32% of anthropogenic carbon dioxide emissions in the U.S. This share could be halved were the coal-fired plants replaced by new plants fired by natural gas, and could be virtually eliminated if we followed the French example and used nuclear power. [12]

c. Global population growth and energy limits.

The third of the major issues to be considered is the problem of matching future energy supplies to the needs of a world population that is growing in numbers and in economic aspirations. The world population was 2.5 billion in 1950 and has risen to about 6 billion today It seems headed to over 10 billion, and perhaps beyond, in the first part of the next century. This growth that inevitably will come up against the obstacle of decreased supplies of oil and gas, and eventually of coal.

The broad problem of resource limitations in the face of a rising population is sometimes couched in terms of the "carrying capacity" of the Earth , or alternatively as the question that provides the title of the very comprehensive 1995 book by Joel Cohen, ***How Many People Can the Earth Support?***[13] But as Cohen himself explains, asking the question so crisply is misleading. In his words [p. 359]:

> While trying to answer the question, I learned to question the question. If an absolute numerical upper limit to human members of the Earth exists, it lies beyond the bounds that humans would willingly tolerate.

One author cited by Cohen puts the matter thus[14]

> The basic definition of sustainability capacity . . . . is: ***the maximum number of persons that can be supported in perpetuity on an area, with a given technology and set of consumptive habits, without causing environmental degradation.***

Or, as put even more succinctly by Garrett Hardin in a review of Cohen's book: [15]

> What one really wants to know is this: after we define the minimally rich sort of life we human beings would consent to live, what is the maximum number of people possible.

Cohen reviews a large number of attempts to estimate the world's ultimate carrying capacity, dating back to the Dutch naturalist Antoni van Leeuwenhoek in 1679. As summarized by Cohen, Leeuwenhoek estimated the population density of Holland to be 120 per km^2, assumed that land encompassed one-third of the Earth's total area, and extrapolated to a world population of about 13 billion.[16] Remarkably, more recent estimates of the Earth's carrying capacity center around a value of about 10 billion, not meaningfully different from the three-century old estimate of Leeuwenhoek. It should be emphasized, however, that the range of estimates is very great---from under 2 billion to well over 20 billion. If one performed today a calculation analogous to that of

Leeuwenhoek, and used national population densities as the guide, the world population extrapolates to 3.6 billion with the United States as the reference base and 3 1 billion with the United Kingdom as the reference.[17]

The constraints that limit world population can be put in several categories:

a. ***Material.*** Population is limited by the accessible supply of necessities and of desired amenities, from food to parking places. Key material factors include land area, energy, and water.

b. ***Ecological.*** Growth in human population places strains on the overall environment, including destruction of wilderness and extinction of other species.

c. Aesthetic orphilosophical. These constraints are suggested, for example, in a quotation from John Stuart Mill, cited by Cohen:**

> A population may be too crowded, though all be amply supplied with food and raiment It is not good for man to be kept perforce at all times in the presence of his species.... Solitude, in the sense of being often alone, is essential to any depth of meditation or of character; and solitude in the presence of natural beauty and grandeur, is the cradle of thoughts and aspirations which are not only good for the individual, but which society could ill do without.

This was written in 1848 when the world population was about one billion

Arguments based on (b) and (c) are difficult to quantify and put in "objective" terms, although in fact they may the most emotionally compelling of all. It is perhaps for this reason that most of the stated rationales for a given carrying capacity are based on material arguments. The most critical material constraint is that of food supply, which in turn depends upon amble land area, energy, and water. In particular, energy is required for irrigation, the production of fertilizers, the operation of farm machinery, and the transportation of farm products.

Even considering only carrying capacity estimates that are based on food limitations, the results differ widely, depending upon the assumptions made as to the area of available land and the average yield per acre obtainable for various sorts of land. In addition, in any such calculation, the magnitude of the required resources is strongly dependent upon the nature of the assumed diet. If much of the caloric intake comes in the form of meat, then considerably more grain production is required than for a largely vegetarian diet with the same total number of calories.[19]

Carrying capacity estimates made directly in terms of energy, in recent papers by David Pimentel and collaborators[20] and by Paul Ehrlich and collaborators,[21] are particularly interesting in the present context as illustrations of the possible implications of restricted energy use. Each group concludes that an optimal global population for a sustainable future is under 2 billion---a much lower limit than given in most other estimates. The argument is made most explicitly in the Pimentel paper. The authors envisage a world in which fossil fuels have been exhausted and solar energy is the only sustainable energy source. They take 35 quad of primary solar energy as the maximum that could be captured each year in the United States. Assuming that the present average per capita U.S. energy consumption is halved through conservation and energy efficiency, the 35 quads would suffice for a population of 200 million. For the world as a whole, reserving some lands for crops, the total available energy would be about 200 quads. If the world per capita energy consumption were to converge to the new U.S. average (one-half the present U.S. average) this would support a population of somewhat over 1 billion, which Pimentel *et al.* interpret as meaning that "1 to 2 billion people could be supported living in relative prosperity."[22]

One can quarrel with the details of this argument, including the maximum assumed for solar energy, the casual dismissal of nuclear fission and nuclear fusion, and the assumption of a much-improved standard living for most of the world population. Nonetheless, it dramatically illustrates the magnitude of the stakes, and the centrality of energy considerations. It is almost impossible to imagine that the world population could shrink to 2 billion from its present 6 billion---and probable future 10 billion---without great social upheavals. Were there really a limit of 200 quads, great conflict and misery would likely mark the path to the future.

An increase in energy supplies would obviously relieve the pressures. In principle, this could be accomplished by more intensive exploitation of renewable energy sources, by expansion of the use of fission energy, by achieving fusion energy, or---with any good fortune---by some combination of these. However, neither the feasibility of fusion energy nor the practicality of very large-scale increases in renewable energy has yet been established. To avoid a tremendous gamble on the economic and social future of the world, it is important to lay the foundation for a substantial expansion in the use of fission energy.

It is neither possible nor necessary to know at this time how far this expansion is to proceed. France, with a population of 60 million, obtains about 4 quad of energy per year from nuclear power---a per capita rate of about 67 MBTU per year. This roughly equals the present average world rate of primary energy consumption from all sources and represents a significant fraction of a possible future world average.[23] Were France's example of nuclear use to be very widely emulated, constraints on uranium supplies would eventually force the adoption of fuel cycles that use uranium (or thorium) more efficiently---such as breeder reactor cycles. But even with present-day light-water reactors, uranium resources suffice for close to a century of operation at about 4 times the present world rate.[24] This in itself would not solve long-term energy problems but could ease the transition, if one is eventually needed, to more resource-efficient nuclear fuel cycles.

To illustrate the options that are made available when there is an ample energy supply, we will consider a rather extreme case---the desalination of sea water. Would it be prohibitively costly to rely on water desalination? It would make little sense to do this in the United States in the predictable future, except in limited local situations, because we are not faced with imminent national water shortages and regional shortages are usually best addressed by more prudent use of existing resources and by transfer from water-rich regions. However, other countries have little alternative to desalination and even in the United States there are already some desalination projects.

To produce one cubic meter of water in future large-scale reverse osmosis plants is expected to cost about $1 and require 6 kWh of electricity.[25,26] Per capita water usage is a little over 2000 m^3 per year in the United States---about three times the world average and more than twice the average for Europe and Japan.[27] If high prices were to lead to a reduction of the U.S. rate to 1000 m^3 per year, then each person's share of the national water budget would be about $1000---showing up in large measure in indirect ways including higher food and electricity costs.[28] To provide this electricity would mean, on a national basis, a 50% increase in total generation. This is a sizable increase, but again not a prohibitive one. It could be accomplished over 40 years with a 1% annual increase in generation per capita (everything else remaining equal). These numbers do not provide an argument for desalination, much less an argument for nuclear energy per se. But they provide an illustration of the ways in which having ample energy supplies can help to ease the support of a larger world population.

Easing the way to a large population is of course not an unmixed blessing. As already suggested there are strong ecological, aesthetic, and philosophical objections to having large further increases in population. At a time when cold fusion was being cited as a potentially unlimited source of energy, Albert Bartlett suggested that "if an abundant source of low-cost energy could be found it may be the worst thing that ever happened to the human race".[29] The specifically cited danger was the temperature rise accompanying untrammeled expansion of energy consumption, but a broader concern is that if mankind has unlimited options the option in the end would be exercised in ways that would severely damage the environment. Unfettered population growth is here probably the greatest single danger.

However, it may be unduly pessimistic to assume that the only choices are between a severely restricted population and a severely damaged environment. It may be possible to find a middle ground in which prudent expansion of the energy supply would allow, say, 10 billion people to live in relative comfort. It will not be easy to accomplish this, nor is it obvious that population growth will stop at 10 billion, or for that matter 20 billion. One approach might be to try to constrict population growth by constricting the energy supplies that make it viable. It is unlikely that so brutal a policy would be adopted by explicit intent. However, forcing the world to forego nuclear energy during the century or two when fossil fuels gradually disappear carries serious dangers. In a world that is short of energy, it is likely that the rich and powerful countries, and the rich and powerful people within those countries, would appropriate the remaining energy supplies and the rest of the world population would suffer the privations attendant upon an energy-poor society.

5. Conclusions.

There is now no significant "nuclear debate" in the United States because nuclear power is dismissed, often without even being mentioned, as not acceptable to the public, not safe, too expensive, or unnecessary---or some combination of these factors. However, attitudes have changed greatly in the past and can again.

If a serious discussion of the role of nuclear power in the nation's and world's energy future is to resume, it should focus on the crucial issues. Of course, it is important to ensure that nuclear reactors are safe---both in design and operation---and that nuclear waste disposal is handled in a responsible fashion. But, as discussed above, the extensive analyses of the risks from nuclear reactors and from nuclear waste disposal provide a basis for confidence that it is possible to make the dangers small.

In contrast, there is a substantial chance that over the next century the world will face critical problems resulting from climate change, nuclear weapons, or a mismatch between world population and world energy supply. It distorts our responsibilities to the future to be almost paralyzed in handling nuclear wastes because of the possibility that they may create very minor risks for a very few people in the very distant future, while neglecting to consider nuclear energy---and energy policy as a whole---in the context of the truly major issues where the stakes are very high.

The most dramatic and probably most immediate, of the dangers are those from nuclear weapons. However, as discussed above, the implications for nuclear power are ambiguous. A heavy commitment to nuclear power, especially if it leads to some versions of a breeder fuel cycle, might increase the chances of nuclear weapons prolifemtion. Conversely, increased nuclear power use might lessen the pressures that lead to conflicts. Turning to the other major areas, the picture is much clearer. Nuclear power can help to reduce carbon dioxide emissions and thereby lessen the severity of predicted climate changes. It could also help ease the difficulties that will arise from the conflict between the shrinking of fossil fuel supplies and the rising material aspirations of a growing world population.

Given the seriousness of the possible consequences of failed energy policies, it is an imprudent gamble to let nuclear power atrophy, in the hopes that renewable energy alone will suffice to solve the problems. It is therefore important to strengthen the foundations upon which a nuclear expansion can be based, so that the expansion can proceed in an orderly manner---if and when it is seen to be needed---rather than with the haste of a crash program. One obvious measure in this direction is the revitalization of university research and educational programs in nuclear energy. But such initiatives will be futile unless there is a belief that the overall enterprise has a future. Important initial steps to make such a belief credible in the United States are progress at Yucca Mountain, within a framework of reasonable nuclear waste disposal standards, and federal encouragement for the construction of prototypes of the next generation of reactors. A reappraisable of the full spectrum of environmental dangers could provide the driving impetus for such a nuclear revival.

FOOTNOTES

[1] For a brief review of this history with literature citations, see: David Bodansky, ***Nuclear Energy: Principles, Practices, and Prospects*** (American Institute of Physics Press/Springer-Verlag, Woodbury NY, 19%).

[2] ***Annual Review of Energy 2997,*** Report DOE/EIA-0384(97) (U.S. Department of Energy, Washington, DC, 1998).

[3] ***Nuclear Power Reactors in the World, April 1998 Edition,*** Reference Date Series No. 2 (International Atomic Energy Agency, Vienna, 1998).

[4] R. J. Belles ***et al.*** "Precursors to Potential Severe Core Damage Accidents: 1997, A Status Report." NUREG/CR-4674 (Washington, D.C.: U.S. Nuclear Regulatory Commission, 1998).

[5] Bodansky, op. ***cit.,*** Section 10.1.

[6] The EPA release limit was set at 100 Ci of ^{14}C per 1000 tonnes of fuel (more precisely, of heavy metals in the fuel). This is about 10% of the total ^{14}C. The release of all the ^{14}C in a repository with, say, 70,000 tonnes of fuel would lead to about 4000 calculated cancer deaths, according to EPA calculations that included a strict application of the linearity hypothesis. The same approach gives a calculated 50,000,000 cancer deaths from ***natural*** ^{14}C in the atmosphere for a population of 10 billion for a 10,000 year period.

[7] ***Technical Bases for Yucca Mountain Standards ,*** Committee on Technical Bases for Yucca Mountain Standards, Robert W. Fri, ch., National Research Council (National Academy Press, Washington DC, 1995).

[8] Michael McCloskey, a former chairman of the Sierra Club is quoted as saying: "I suspect many environmentalists want to drive a final stake in the heart of the nuclear power industry before they will feel comfortable in cooperating fully in a common effort at solving the waste problem..... Their concern would arise from the possibility that a workable solution for nuclear waste disposal would make continued operation of existing plants more feasible, and even provide some encouragement for new ones." [Luther Carter, ***Nuclear Imperatives and the Public Trust*** (Resources for the Future, Washington DC, 1987), p. 431].

[9] Highly enriched ^{235}U was used for the U.S. bomb dropped on Hiroshima, for the first bomb tested by China, for the first weapons efforts of Pakistan, and for the since-abandoned weapons programs of Argentina, Brazil, and South Africa.

[10] The fuel removed from reactors contains large amounts of plutonium. The large ^{240}Pu admixture in "reactor-grade" plutonium makes it difficult to build a bomb, but not impossible to do so. The very high level of radioactivity of the spent fuel provides a protective barrier against diversion of the fuel by any group that lacks extensive facilities for handling and transporting the fuel, greatly complicating potential clandestine diversion attempts.

[11] ***IPCC Second Assessment: Climate Change 1995,*** A report of the Intergovernmental Panel on Climate Change (World Meteorological Organization and UN Environment Programme, 1995).

[12] For 1997, the CO_2 emissions were: 32% from coal in electricity generation, 4% from oil and gas in electricity generation, 32% from oil (and a small amount of gas) in transportation; and 32% from fossil fuel use in industry, commercial activities, and residence. [Ref: *Emissions of Greenhouse Gases in the United States: 2997,* Report DOE/EIA 0573(97) (U.S. DOE, Washington DC, 1998).] The replacement of fossil fuels is simplest in electricity generation, but gains are possible in the other sectors through conservation and electrification.

[13] Joel E. Cohen, *How Many People Can the Earth Support?"* (W.W. Norton & Co, New York, 1995).

[14] Philip Feamside, as quoted by Cohen, op. *cit.,* p. 421.

[15] Garrett Hardin, review of "How Many People Can the Earth Support," by Joel E. Cohen, *Population and Environment, a Journal of Interdisciplinary Studies, 18,* no. 1 (Sept. 1996), 73-76.

[16] This sort of analysis embodies what has come to be known as the "Netherlands fallacy." The fallacy lies in ignoring the dependence of densely populated areas, such as the Netherlands, on imports from less densely populated areas--including food.

[17] Using the UK as a reference of course repeats the Netherlands fallacy (see above). It should be noted that these are not extreme reference cases. Taking Bangladesh as the reference gives a population of 99 billion and taking Australia gives 0.3 billion.

[18] From *Principles of Political Economy* by John Stuart Mill, as quoted by Cohen, op. *cit.,* p. 197.

[19] For a given caloric intake, roughly ten times as much grain must be grown if the calories are from meat rather than if directly from the grain (Cohen, op. *cit..,* p. 310). Using this rough estimate for an illustrative calculation, a diet in which 20% of the calories come from meat requires almost three times as much grain as does a vegetarian diet. [Note: 0.8 + 0.2 x 10 = 2.8.)

[20] David Pimentel *et al,* "Natural Resources and Optimum Human Population, *Population and the Environment, A journal of Interdisciplinary Studies* 15, no. 5 (May 1994), 347 - 69.

[21] Gretchen C. Daily, AM H. Ehrlich and Paul R. Ehrlich, "Optimum Human Population Size," *Population and the Environment, A Journal of Interdisciplinary Studies 15,* no. 6 (July 1994), 469 - 475.

[22] A population of 2 billion would correspond to an annual per capita consumption rate of 100 **MBTU** , compared to the rate of 175 MBTU projected for the U.S.

[23] Per capita energy consumption rates in 19% averaged 400 MBTU for the United States, 200 MBTU for France, under 40 MBTU for China, and about 80 MBTU for the world. For some countries in the developing world this does not include contributions from wastes and other forms of biomass.

[24] World resources of uranium at $100 per pound of uranium oxide (equivalent to about 0.6 cents/kWh) are in the rough neighborhood of 20 million tonnes, sufficient for about 100,000 gigawatt-years of operation.

[25] Juergen Kupitz, "Nuclear energy for seawater desalination: Updating the record," *IAEA Bulletin 37,* no. 2, 21-24 (1955).

[26] L. Breidenbach, 'Thermo-economic evaluation of a nuclear plant for electricity and potable water,"

in ***Nuclear Desalination of Sea Water,*** Proceedings of an International Symposium on Desalination of Seawater with Nuclear Energy, Organized by the International Atomic Energy Agency, Taejon, South Korea, May 26-30, 1997 (IAEA, Vienna, 1997).

[27] This is the total rate of water withdrawal in the country from all sources and for all purposes, divided by the total population. See: ***Water in Crisis,*** Peter H. Gleick, ed. (Oxford University Press, New York, 1993), Section H.

[28] As a point of comparison, lest this seem "prohibitive," we can note that in 1981, when oil prices were at their peak, the average per capita expenditures for motor gasoline and other petroleum products was $1900 (expressed in 1997 dollars).

[29] Albert A. Bartlett, "Fusion and the Future," ***Physics and Society*** 18, no. 3, 11-12 (July 1989).