Summary

Insurmountable Risks:

The Dangers of Using Nuclear Power to Combat Global Climate Change

Brice Smith

A Report by the Institute for Energy and Environmental Research

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This booklet summarizes the main findings and conclusions from *Insurmountable Risks: The Dangers of Using Nuclear Power to Combat Global Climate Change* by Brice Smith, Ph.D. published by IEER Press.

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> By the end of the century, climate change and its impacts may be the dominant direct driver of biodiversity loss and changes in ecosystem services globally.... The balance of scientific evidence suggests that there will be a significant net harmful impact on ecosystem services worldwide if global mean surface temperature increases more than 2° Celsius above preindustrial levels or at rates greater than 0.2° Celsius per decade (medium certainty).[1]
>
> - United Nations Millennium Ecosystem Assessment (2005)

> The potential impact on the public from safety or waste management failure and the link to nuclear explosives technology are unique to nuclear energy among energy supply options. These characteristics and the fact that nuclear is more costly, make it **impossible** today to make a credible case for the immediate expanded use of nuclear power.[2]
>
> - *The Future of Nuclear Power*, MIT (2003)

Section S.1 - The Threat of Global Climate Change

Climate change is by far the most serious vulnerability associated with the world's current energy system. Outside of full scale thermonuclear war, it is perhaps the largest single environmental threat of any kind confronting humanity today. The Intergovernmental Panel on Climate Change (IPCC), an organization of the world's leading climate scientists chartered through the World Meteorological Organization and the United Nations Environment Program, has concluded that the current level of carbon dioxide in the atmosphere is higher than it has been in at least the last 420,000 years, and is likely the highest it has been in the past 20 million years. By the end of this century, the IPCC predicts that the Earth's temperature will have increased by an average of 1.4 to 5.8 ^{o}C.[3] When considering the relative costs, benefits, and risks of strategies to reduce greenhouse gas emissions, it is important to keep in mind how serious the impacts of climate change might be if we do not act aggressively.

With global warming comes such possibilities as an increased intensity and frequency of storms and natural disasters such as hurricanes, floods, and droughts, heightened pressures on ecosystems and agricultural capacity, and changing patterns of disease. The IPCC notes that the "frequency and magnitude of many extreme climate events increase even with a small temperature increase" and that such increases "can cause critical design or natural thresholds to be exceeded, beyond which the magnitude of impacts increases rapidly."[4] The 2004 and 2005 hurricane seasons in the Atlantic provided particularly stark illustrations of the damage that can accompany unusually severe storm seasons.

The IPCC estimates that approximately 25 percent of the world's mammals and 12 percent of the world's birds are already facing "a significant risk of global extinctions."[5] In the future, the IPCC predicts that, "[t]he risk of extinction will increase for many species, especially those that are already at risk due to factors such as low population numbers, restricted or patchy habitats, limited climatic ranges, or occurrence on low-lying islands or near the top of mountains."[6] The United Nations' 2005 Millennium Ecosystem Assessment concluded that "[b]y the end of the century, climate change and its impacts may be the dominant direct driver of biodiversity loss and changes in ecosystem services globally."[7] The Arctic is likely to be one of the areas most heavily affected by global warming. As noted by the intergovernmental Arctic Council, "[p]olar bears are unlikely to survive as a species if there is an almost complete loss of summer sea-ice cover, which is projected to occur before the end of this century by some climate models."[8] When the impacts on polar bears are added to the impacts of climate change on sea ice dependent seals and birds and to the impacts on tundra dwelling animals like caribou, global warming is expected to dramatically affect the lives of many arctic residents, particularly Indigenous Peoples.

In addition to changes in global temperatures, the dissolution of atmospheric carbon dioxide in the world's oceans is already causing the water to become increasingly acidic. Decreases in ocean pH as a result of dissolved CO_2 have a number of negative effects on marine life, and are a particular threat to organisms that rely on calcium-based shells like coral.[9] As summarized by the British Royal Society

> Without significant action to reduce CO_2 emissions into the atmosphere, this [ocean acidification] may mean that there will be no place in the future oceans for many of the species and ecosystems that we know today. This is especially likely for some calcifying organisms [such as coral].[10]

Finally, the IPCC found that changes in the global climate system would have a number of direct and indirect effects on human health. Some of these direct effects would be positive such as a decrease in cold related deaths. Others, however, would be negative such as an increase in heat related deaths and changes in the geographic distribution of diseases. In addition to these direct effects, there would be indirect effects such as changes to food production patterns and an intensification of natural disasters like floods and droughts. Overall, the IPCC concluded that "negative health impacts [of global warming] are anticipated to outweigh positive health impacts."[11] The World Health Organization reached a similar conclusion in its 2003 review.[12]

Even more serious consequences could arise as a result of rapid changes to the climate. One example of a potential rapid change would be the weakening or total shutdown of the thermohaline circulation, a complex series of ocean currents that transport heat from the equatorial latitudes northwards in the Atlantic Ocean. While the average temperature of the world would continue to rise, a shutdown of the thermohaline circulation would cause temperatures in northern and western Europe to drop significantly.[13] As summarized by the National Research Council of the U.S. National Academy of Sciences

> Abrupt climate changes were especially common when the climate system was being forced to change most rapidly. Thus, greenhouse warming and other human alterations of the earth system may increase the possibility of large, abrupt, and unwelcome regional or global climactic events. The abrupt changes of the past are not fully explained yet, and climate models typically underestimate the size, speed, and extent of those changes. Hence, future abrupt changes cannot be predicted with confidence, and climate surprises are to be expected.[14]

While there are significant uncertainties surrounding the potential consequences of global warming, the possible outcomes are so varied and potentially so severe in their ecological and human impacts that immediate precautionary action is called for in order to try and mitigate the damage being done to the Earth's climate. Definitive proof will only come following a catastrophe, and by then it will be too late to effectively take action. The potential impacts of global warming, combined with our rapidly evolving understanding of the climate system provides a strong motivation to prioritize mitigation strategies that will have the largest likelihood of making significant contributions in the near to medium-term while not jeopardizing the future implementation of more equitable and sustainable long-term strategies. It is in this light that we have examined the question of what strategies might play a role in combating the threat of global climate disruption.

Compared to the other major energy sources used around the world to generate base load electricity such as coal, oil, and natural gas, nuclear power plants emit far lower levels of greenhouse gases even when mining, enrichment, and fuel fabrication are taken into consideration.[15] As a result of this fact, some have come to believe that nuclear power may be able to play an important role in efforts to reduce emissions from the electricity sector while simultaneously increasing supply. To examine the implications of such strategies, we chose to consider two representative scenarios for the future expansion of nuclear power.

The first scenario was taken from a 2003 study from the Massachusetts Institute of Technology entitled *The Future of Nuclear Power*. In this interdisciplinary report, the authors begin with the important acknowledgement that

> The generation of electricity from fossil fuels, notably natural gas and coal, is a major and growing contributor to the emission of carbon dioxide -- a greenhouse gas that contributes significantly to global warming. We share the scientific consensus that these emissions must be reduced and believe that the U.S. will eventually join with other nations in the effort to do so.[16]

The authors go on to envision a "global growth scenario" for nuclear power with a base case of 1,000 gigawatts (GW) of capacity installed around the world by 2050. Since all of the reactors in operation today would be shutdown by mid-century, the net increase represented by the MIT global growth scenario over today's effective capacity would be roughly 230 percent.[17] To give a sense of the scale of this proposal, the MIT scenario would require a new 1,000 megawatt (MW) reactor to come online somewhere in the world every 15 days on average between 2010 and 2050. As noted by the authors of the MIT report, "[t]he implied construction rate near the mid-century endpoint of the global growth scenario would be challenging and exceed any rate previously achieved."[18]

Despite the large increase in nuclear capacity under the MIT global growth scenario, the demand for electricity under their projections would grow rapidly enough that the carbon emissions from the electricity sector would continue to increase over the coming decades. In the United States, for example, where the largest share of nuclear construction is assumed to occur, we estimate that, under the global growth scenario, the carbon emissions from electricity production in 2050 would ***increase*** by approximately 13 to 62 percent over their year 2000 levels. In order to consider the implications of a scenario in which a more serious effort would be made to limit carbon emissions through the expanded use of nuclear power, we developed an alternative scenario which we call the "steady-state growth scenario."

Using the same level of projected growth in electricity demand considered by the authors of the MIT report, we calculated the number of nuclear reactors that would be required in 2050 in order to simply ***maintain*** the carbon emissions from the electricity sector at their year 2000 levels.[19] Making a range of assumptions about the future contribution of renewables (20 to 40 percent of total generation in 2050) and about the future contribution of natural gas fired plants (1.5 to 2.5 times the current level of generation), we find that between 1,900 and 3,300 gigawatts of nuclear capacity would be required world wide just to hold emissions constant. For simplicity we have used a value of 2,500 gigawatts of nuclear power as our alternative case study.[20]

The large number of reactors required for nuclear power to play any meaningful role in reducing greenhouse gas emissions greatly complicates the efforts required to deal with its unique vulnerabilities including the potential for the nuclear fuel cycle to enable nuclear weapons proliferation, the risks from catastrophic reactor accidents, and the difficulties of managing long-lived and highly radiotoxic nuclear waste. The rapid rate of nuclear construction required to meet the global or steady-state growth scenarios would also put great pressures on the nuclear industry as well as on regulatory bodies and make it more difficult to achieve or sustain the substantial improvements in cost that have been envisioned by nuclear proponents. The scenarios we have considered are not extreme cases given the rate of demand growth assumed in the MIT analysis. For example, under the global growth scenario nuclear power would make up 19.2 percent of the world's electricity in 2050 compared to 16.3 percent in the year 2000.[21] Under the steady-state growth scenario, nuclear power would supply 48.1 percent of global electricity demand in 2050, which is comparable to coal's share of U.S. electricity production in 2000.[22]

As more is learned about the functioning of the Earth's climate, the more likely it appears that reductions in greenhouse gas emissions on the order of 60 to 80 percent will be required by 2050 to avoid the more serious consequences of global warming. As such, a number of aggressive policies will be needed in the coming decades to curb and then reverse the growth of CO_2 emissions from all sectors of the energy system. Adding to the complexity of this already extremely difficult problem is the fact that these reductions will have to occur at a time of increasing electricity demand throughout the Global South. Of particular note is the projected increase in electricity demand in the world's two most populous countries, India and China.

Given that both time and resources are limited, a choice must be made as to which alternatives should be pursued aggressively and which should play only a small role or be put aside all together. Given the immediacy of the problem, it will be necessary to consider options that are available for immediate use as well as those that can confidently be brought online within then next five to fifteen years. The best mix of alternatives will vary according to local, regional, and country specific resources and needs. As such, the details of the future energy system cannot yet be completely foreseen in all cases.[23] However, in making a choice among alternatives, the following considerations should serve to guide the selection: (1) the options pursued must be capable of making a significant contribution to a reduction in greenhouse gas emissions, with a preference given to options that achieve more rapid reductions; (2) the options should be economically competitive to facilitate their rapid entry into the market; (3) the options should, to the extent consistent with the goals of reducing the threat from climate change, minimize other environmental and security impacts; and finally (4) the options should, to the maximum extent possible, be compatible with the longer term goal of creating an equitable and sustainable global energy system. It is within this context that the future of nuclear power must be judged. As such we must carefully consider the cost of electricity from new nuclear plants as well as the environmental, health, and security implications of the global and steady-state growth scenarios in order to determine how the nuclear option compares to other available alternatives.

Section S.2 - From "too cheap to meter" to "just too expensive"

The first thing to note when considering the future cost of nuclear power is that it is a "mature" technology that has already been commercialized for more than half a century. Currently, 103 nuclear plants are online in the U.S. alone, and a total of 438 reactors are in existence around the world.[24] In 1954 then AEC Commissioner Lewis Strauss promised the world that "[i]t is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter."[25] Over the next 50 years, nuclear power received more government support and subsidization in the United States than any other source of electricity. Despite this intense support, however, the large cost overruns and ballooning lead times for construction in the U.S. made nuclear power an economically unattractive option over time (see Figure ES.1).

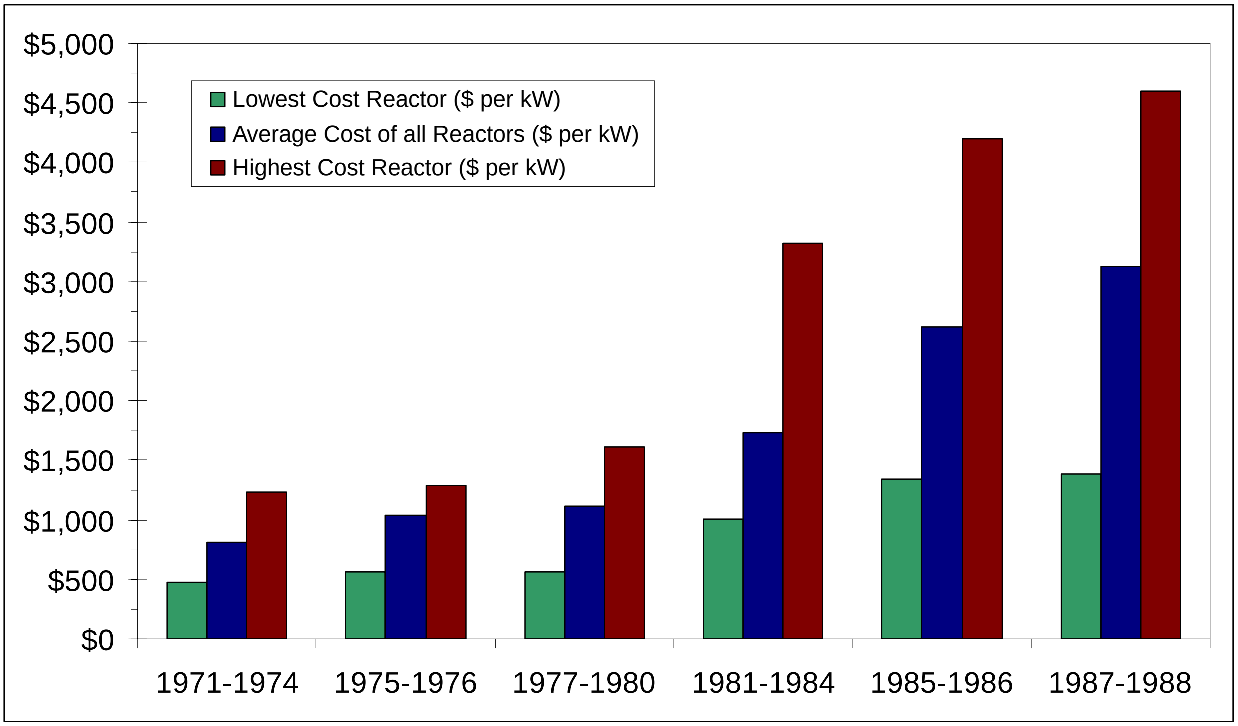

Figure ES.1: Overnight cost of commercial nuclear reactors built in the United States grouped by the date in which they entered operation (all figures in 1988 dollars). The difference between the cost of the most expensive and least expensive reactors completed in the 1980s was more than three and a half times the average cost of the reactors completed in the 1970s.[26]

By the mid-1980s the rising and increasingly uncertain cost of nuclear construction led a Forbes Magazine cover story to conclude that "[t]he failure of the U.S. nuclear power program ranks as the largest managerial disaster in business history, a disaster on a monumental scale."[27] As a result of this poor economic performance, combined with an erosion of public support due to concerns over reactor safety and nuclear waste management, no new reactors have been ordered in the U.S. in more than a quarter of century and no new reactor has come online in nearly a decade. Despite a number of significant improvements that have been made since the 1980s, electricity from new nuclear power plants is expected to remain an expensive option. For example, projections from the 2003 MIT study and a 2004 study from the University of Chicago put the likely cost of electricity from new nuclear power plants well above the cost of electricity from natural gas or pulverized coal fired plants (see Table ES.1).

Table ES.1: Levelized cost of electricity (in cents per kWh) from new nuclear power, pulverized coal, and natural gas fired power plants as estimated by the MIT and University of Chicago studies.[28]

Generation Type	MIT Report	University of Chicago Report
Pulverized Coal[(a)]	4.2	3.3 to 4.1
Natural Gas (CCGT)[(b)]	3.8 to 5.6	3.5 to 4.5
Nuclear Power[(c)]	6.7	6.2

(a) Levelized cost of coal in the MIT study is $1.30 per million Btu (MMBtu) while the average price of coal over the lifetime of the plants in the U Chicago study is $1.02 to $1.23 per MMBtu.

(b) Levelized cost of natural gas in the MIT study is $3.77 to $6.72 per MMBtu. The average price of natural gas over the lifetime of the plants in the U Chicago study is $3.39 to $4.46 per MMBtu. The price for natural gas has fluctuated a great deal in recent years and has been both above and below the range considered here at times. For comparison, the average price of natural gas sold to the electric power sector was $6.11 per thousand cubic feet in 2004 and $8.45 per thousand cubic feet in 2005.[29] However, long-term gas prices can be expected to remain within the range considered by the authors of the MIT study if policies on efficiency, conservation, and an increased reliance on liquefied natural gas are pursued.

(c) Overnight capital cost of a nuclear plant in the MIT study is $2,000 per kW. While the U Chicago analysis considered a range of capital costs from $1,200 to $1,800 per kW, the lower end of this range was so far out of what could be reasonably expected from experience in the U.S. and around the world that we did not consider it to be a credible basis for analysis. The middle of the U Chicago range, $1,500 per kW, was used as the basis for our economic analysis.

From our analysis of the overnight capital cost, lead time for construction, and interest rate premium charged by financial institutions due to the higher risk of nuclear construction, we have concluded that it is most likely that the cost of electricity from future nuclear power plants will fall within the range of six to seven cents per kWh. While a number of potential cost reductions have been considered, it is unlikely that plants not heavily subsidized by the federal government would be able to achieve any further improvements beyond those already incorporated into the base case estimates from Table ES.1.[30] This is particularly true given that any improvements would have to be maintained under the very demanding timetables set by the global or steady-state growth scenario. As summarized by the authors of the MIT report themselves,

> The bottom line is that with current expectations about nuclear power plant construction costs, operating costs and regulatory uncertainties, it is extremely unlikely that nuclear power will be the technology of choice for merchant plant investors in regions where suppliers have access to natural gas or coal resources. **It is just too expensive.**[31]

While it is important to realize that electricity from new nuclear power plants is likely to be substantially more expensive than electricity from either coal or natural gas, even when optimistic improvements over historical experience are considered, this comparison is not necessarily the one most relevant to the current discussion of what role nuclear power might play in mitigating the impacts of climate change. The more important question in the present context, is how the economics of nuclear power compare to those of alternative strategies for reducing carbon emissions. However, before moving on to a consideration of what those alternatives might be, we first had to consider what the environmental, health, and security impacts of the global and steady-state growth scenarios would be in order to have a more complete basis against which to compare the nuclear option.

Section S.3 - Megawatts and Mushroom Clouds

While concerns over catastrophic accidents and long-term waste management have received more public attention, the largest single vulnerability associated with an expansion of nuclear power is likely to be its potential connection to the proliferation of nuclear weapons. As summarized nearly sixty years ago by the U.S. Committee on Atomic Energy, "[t]he development of atomic energy for peaceful purposes and the development of atomic energy for bombs are in much of their course interchangeable and interdependent."[32] This overlap between the nuclear fuel cycle and the infrastructure required to produce fissile materials for nuclear weapons makes nuclear power a uniquely dangerous source of electricity. The authors of the MIT report themselves conclude that "[n]uclear power should not expand unless the risk of proliferation from operation of the commercial nuclear fuel cycle is made acceptably small."[33] However, the proposals that have been put forth to try and reduce the risks of proliferation are very unlikely to be successful in a world where the five acknowledged nuclear weapons states seek to retain their arsenals indefinitely and to continue to explicitly rely on them as a central element of their security policies.

For light-water reactors, the type of reactor most likely to dominate any nuclear revival, uranium enrichment forms a vital step in the front end of the nuclear fuel cycle. While the 14 enrichment plants in operation today are capable of fueling the existing fleet of reactors, all of these facilities would have to be replaced over the next few decades if nuclear power were to be significantly expanded. The planned closure of the two large gaseous diffusion plants in the U.S. and France, which together account for nearly half of the world's current enrichment capacity, and their replacement by smaller gas centrifuge plants would be of particular importance. In order to fuel the number of nuclear plants envisioned under the global or steady-state growth scenarios, increases in the world's uranium enrichment capacity of approximately two and half to six times would be required. Another way to appreciate the magnitude of the required capacity is to note that, fueling the global growth scenario alone would require approximately 18 times more enrichment capacity than is currently deployed by Urenco in all of Britain, Germany, and the Netherlands combined.[34]

The development of such a large number of enrichment plants would create three types of proliferation risks. The first relates to the diversion of weapons usable material from known facilities that are ostensibly intended for civilian purposes. The South African weapons program is an example of this proliferation pathway. The second concern relates to the construction and operation of a dedicated, clandestine facility for strictly military purposes using technology initially developed for commercial applications. The Pakistani program illustrates the dangers of this second proliferation route. Third, there is the possibility that stockpiles of low-enriched uranium and the existence of commercial enrichment facilities could allow rapid weaponization in the future should a country so choose. To date, no country has yet followed this third route to the acquisition of nuclear weapons, but the potential "latent nuclear deterrent" of enrichment capabilities, as it was called by IAEA Director General Mohamed ElBaradei, is clearly apparent in the ongoing negotiations surrounding the Iranian enrichment program.[35] To give a sense of the magnitude of these risks, just <u>one percent</u> of the enrichment capacity required by the global growth scenario would be enough to supply the highly-enriched uranium for nearly 210 nuclear weapons every year.[36]

The requirements for enrichment would be decreased somewhat if a portion of the spent fuel were reprocessed and the separated plutonium was fabricated into MOX fuel. However, the amount of enrichment services required would remain significantly above presently available levels. For example, the authors of the MIT study found that the optimal use of MOX would reduce future enrichment needs by only 16 percent. In addition to the need for a large increase in enrichment capacity, the separation of weapons usable plutonium under such a scenario would add significantly to the proliferation risks of such a nuclear revival. The existing commercial reprocessing capacity is well below what would be needed to support the widespread use of the MOX fuel cycle. For example, even if just 16 percent of the fuel requirements were met by MOX, as assumed by the authors of the MIT study, a reprocessing capacity three and a half to nine times greater than that in existence today would be required in order to support the global or steady-state growth scenarios.

Assuming a 75 percent capacity factor for the reprocessing plants, the global growth scenario would require more than 17 plants the average size of the existing La Hague, Thorp, and Rokkasho reprocessing plants. For the steady-state growth scenario a total of 43 such reprocessing facilities would be required. Under just the global growth scenario, more than 155 metric tons of plutonium would be separated annually in order to supply the required MOX fuel. At this rate, more commercial plutonium would be separated every two years than the total amount produced since 1945 for both the U.S. and Soviet militaries combined.[37] In fact, just <u>one percent</u> of this commercial plutonium would be sufficient to produce more than 190 nuclear weapons every year.

The difficulties that have been experienced to date in accounting for plutonium at existing reprocessing and fuel fabrication facilities add to the risks of using the MOX fuel cycle. For example, in 2003 the Japanese government admitted that the Tokai-mura pilot reprocessing plant could not account for some 206 kilograms of plutonium that it had processed. This was on top of the 70 kilograms of plutonium that remain unaccounted for at a Japanese plutonium fuel fabrication facility. In 2003 and 2004 alone, the British Thorp reprocessing plant reported that it could not account for 49 kilograms of plutonium.[38] While newer reprocessing technologies like UREX+ or pyroprocessing would have some advantages over the current PUREX process from a proliferation standpoint, the resulting plutonium would still be usable in nuclear weapons, making them a serious concern. In addition, materials accounting at pyroprocessing facilities would likely be even more difficult than at current plants, making clandestine diversion even harder to detect.

As the withdrawal of North Korea from the Nuclear Non-Proliferation Treaty (NPT) and its apparent resumption of nuclear weapons production have shown, even if inspections and treaty obligations were able to prevent current weapons activity, they are not always a guarantee for the future. A further example of how the international situation may change dramatically over time is the case of Iran. In the mid-1970s the United States was allied with the Shah of Iran and sought to encourage not only the development of nuclear power plants in Iran, but also commercial scale fuel cycle facilities as well. The limitation of treaty obligations to deter future military use of supposedly civilian infrastructure was highlighted as early as 1946 by J. Robert Oppenheimer. Speaking on the likely U.S. response to signing a treaty to abolish nuclear weapons, Dr. Oppenheimer stated that

> We know very well what we would do if we signed such a convention: we would not make atomic weapons, at least not to start with, but we would build enormous plants, and we would call them power plants - maybe they would produce power: we would design these plants in such a way that they could be converted with the maximum ease and the minimum time delay to the production of atomic weapons, saying, this is just in case somebody two-times us; we would stockpile uranium; we would keep as many of our developments secret as possible; we would locate our plants, not where they would do the most good for the production of power, but where they would do the most good for protection against enemy attack.[39]

As a result of the inability of all but the most highly intrusive, expensive, and time consuming inspection regimes to prevent proliferation of nuclear weapons, as well as the possibility that states could pull out of safeguards in the future and use formerly civilian infrastructure for weapons production, the Bush Administration and the IAEA now seek to restrict access to these fuel cycle technologies. These proposals have been put forth despite the clear language in Article IV of the Nuclear Nonproliferation Treaty which gives any member in good standing with the IAEA the right to posses uranium enrichment and reprocessing facilities as part of a civilian nuclear power program.

Proposals to create national or international monopolies on the nuclear fuel cycle are very unlikely to be acceptable. The implication of these proposals is, in effect, that certain countries, including the only country to have used nuclear weapons in a time of war, can be trusted with the fuel cycle while no one else can. This is clearly a highly discriminatory policy, and not one likely to gain significant support. The deadlock at the 2005 NPT Review Conference in New York and the continued refusal of Iran to abandon the development of an indigenous enrichment capability are clear examples of the difficulties faced by any attempt to prevent countries from controlling the production of their own nuclear fuel. This difficulty would be greatly increased under the global or steady-state growth scenarios given the increased reliance on nuclear power of many countries that do not currently posses fuel cycle facilities. However, even if such a restrictive proposal could somehow be brought into force, it would still not be capable of eliminating the proliferation risks associated with a large expansion of nuclear power. As Mohamed El-Baradei has noted

> The technical barriers to mastering the essential steps of uranium enrichment – and to designing weapons – have eroded over time, which inevitably leads to the conclusion that the control of technology, in and of itself, is not an adequate barrier against further proliferation.[40]

The extent of the A.Q. Khan proliferation network, and fact that it was reportedly able to transfer advanced centrifuge technology and components from Pakistan to Iran, Libya, and North Korea before it was stopped, highlights the limitations of export controls and other efforts to prevent clandestine proliferation. Such concerns have given rise to an increased focus by some on punishing proliferation after it has been discovered.

The use of punitive sanctions or military intervention in order to enforce restrictions on access to fuel cycle technologies would add greatly to the unacceptability of such proposals. These kinds of actions would further the discriminatory nature of these strategies. Specifically, the five acknowledged nuclear weapons states, which are also the five permanent members of the Security Council, along with their allies would be shielded from any negative consequences. The embracing of "preemptive" military strikes by powerful states like the U.S. and Israel (which have both demonstrated their willingness to carry out such a policy in defiance of international opinion), further erodes the acceptability of such proposals. Nuclear power would be a very unattractive option if the proliferation of nuclear weapons was held in check by increased regional tensions, sanctions that most directly hurt ordinary people, and a heightened risk of conventional war.

Finally, the inability to adequately address the problem of countries outside the NPT regime, and the inability to address the unwillingness of the five weapons states to live up to their NPT obligation to disarm severely limits the effectiveness of any effort to prevent nuclear weapons proliferation while expanding nuclear power.[41] The institutionalization of a system in which some states are allowed to possess nuclear weapons indefinitely while dictating intrusive inspections and restricting what activities other states may pursue is not sustainable. As summarized by Mohamed ElBaradei

> We must abandon the unworkable notion that it is morally reprehensible for some countries to pursue weapons of mass destruction yet morally acceptable for others to rely on them for security – indeed to continue to refine their capacities and postulate plans for their use.[42]

Without a concrete, verifiable program to irreversibly eliminate the tens of thousands of existing nuclear weapons, no nonproliferation strategy is likely to be successful, no matter how strong it would otherwise be. As such, the link to nuclear weapons is likely to prove to be one of the most difficult obstacles to overcome in any attempt to revive the nuclear power industry.

Section S.4 - Playing Russian Roulette

In addition to its link to nuclear weapons proliferation, the potential for a catastrophic reactor accident or well coordinated terrorist attack to release a large amount of radiation makes nuclear power a uniquely dangerous source of electricity. Such a release could have extremely severe consequences for human health and the environment, would require very expensive cleanup and decontamination efforts, and would leave buildings and land dangerously contaminated well into the future. Adding to the uncertainty of estimating the potential impacts of such accidents is the fact that the last systematic analysis released by the U.S. government was completed nearly a quarter of a century ago. That study, entitled Calculation of Reactor Accident Consequences for U.S. Nuclear Power Plants (CRAC-2) conducted at Sandia National Laboratories, found that a worst case accident at many power plants could cause tens of thousands of deaths from prompt radiation effects and long-term fatal cancers and cause hundreds of billions of dollars in damage. While an accident under typical weather conditions would have much lower consequences, the damage at some plants could still exceed the Price-Anderson Act's current liability limit of $10.9 billion.[43] In addition, it is important to keep in mind the lesson learned from the release of toxic methyl isocyanate gas at the Union Carbide plant in Bhopal, India, which killed nearly 4,000 people and injured 200,000, namely that sometimes a worst case accident can, in fact, occur.[44]

Even if a reactor's secondary containment was not breached, however, and there were not dangerously large offsite releases of radiation, a serious accident would still cost the utility a great deal due both to the loss of the reactor and the need to buy replacement power until new generating capacity could be built. As summarized by Peter Bradford, a former commissioner of the Nuclear Regulatory Commission,

> The abiding lesson that Three Mile Island taught Wall Street was that a group of N.R.C.-licensed reactor operators, as good as any others, could turn a $2 billion asset into a $1 billion cleanup job in about 90 minutes.[45]

So far, there have been a total of seven reactor accidents that have resulted in the release of radiation. These accidents have occurred at both military and civilian reactors that employed a variety of different designs. While light-water reactors make up the majority of current generating capacity, it is important to note that they were not chosen on the basis of their safety. As summarized by Alvin Weinberg, the director of Oak Ridge National Laboratory from 1955 to 1973, "in those earliest days we almost never compared the intrinsic safety of the LWR with the intrinsic safety of its competitors."[46]

To date, the worst reactor accident to have occurred was the April 26, 1986, steam explosion at the graphite moderated, water-cooled Chernobyl nuclear power plant. An estimated 220,000 people were forced to relocate following the accident and large areas of agricultural land had to be abandoned. Several thousand people across Europe and the former Soviet Union are ultimately expected to die as a result of this disaster. So far, the most serious accident to have occurred at a commercial light-water reactor was the March 1979 partial meltdown at Three Mile Island. Although this accident is not officially believed to have resulted in the release of large quantities of non-noble gas radionuclides to the environment, as Richard Feynman famously noted in relation to the O-ring failures that led to the destruction of the Space Shuttle Challenger, "[w]hen playing Russian roulette, the fact that the first shot got off safely is of little comfort for the next."[47]

The rate of accidents at nuclear plants is expected to follow what David Lochbaum has called the "bathtub curve."[48] Specifically, the accident rate is expected to be higher during the initial shakedown phase when the plant is new. As the equipment is tested and broken in and the operators gain experience, the failure rate is expected to fall until it reaches a relatively steady rate where it remains for a majority of the plant's operation. Eventually the equipment in the plant begins to age and wear out while the operator's accumulation of experience has the potential to lead to over-confidence. During this wear-out stage, the accident rate will begin to rise and grow over time until the plant is finally shut down. The average failure rate over the whole lifetime of the plant is the parameter of most interest in determining the risk, and will not be accurately reflected by ignoring the higher values during either the shakedown or wear-out phases.

All seven nuclear accidents to have occurred so far have happened within one to seven years of the reactors first achieving criticality. Overall, the average length of time that these reactors had been operating before suffering their respective accidents was less than three and a half years. As the current fleet of reactors has aged, the number of incidents caused by equipment wearing out has grown. So far, the most important example of the degradation of safety due to aging has been the corrosion of the reactor vessel head at the Davis-Besse plant near Toledo, Ohio. During inspections in March 2002, the operator of the plant discovered that boric acid, leaking from inside the core, had eaten a hole roughly the size of a pineapple through the carbon steel top of the reactor vessel. As a result, the only material left to contain the superheated cooling water, exerting more than 2,180 pounds per square inch of pressure, was a stainless steel liner just 0.125 inches thick. If this lining had ruptured, it could have damaged the nearby control rod and would have led to a potentially serious loss of coolant accident.

Both the NRC's "Lessons Learned" Task Force and the U.S. Government Accountability Office concluded that the corrosion of the vessel head could have been prevented if the NRC and the reactor operators had acted properly. At least twice, the operators of the Davis-Besse plant put off careful examination of the vessel despite identification of possible boric acid leaks. Following these revelations, NRC Chairman Richard Meserve concluded that "[i]n short, the inspections at Davis-Besse have revealed that the head corrosion problem was a direct result of a degraded safety culture" and that "a recurrent theme over the past decade is the need for improvement of safety culture at plants that are encountering serious difficulties."[49]

The inclusion of so-called regulatory insurance in the 2005 Energy Policy Act raises new concerns about NRC oversight during the licensing of new nuclear plants. Under this law, the government could reimburse utilities for a total of up to $2 billion for the first six new plants if legal challenges or NRC safety reviews were to delay the plants' construction. As such, this law will effectively punish the NRC for carrying out its responsibility to protect the public health. The NRC will be particularly hard pressed to justify a delay, given that the government is already running a record deficit. Unlike most subsidies which simply transfer public money to private hands, this subsidy would have a chilling effect on regulators and would further weaken the oversight provided by the NRC.

In addition, the failure of the DOE to open a permanent high-level waste repository and the decision by the utilities to leave spent fuel in densely packed cooling pools has resulted in pools at many older reactors containing several times more long-lived fission products like cesium-137 and strontium-90 than is contained in the reactors' cores. If the cooling water in the pool was somehow lost, the fuel's zirconium cladding could ignite and result in a fire that would release large amounts of volatile fission products. Such a release could contaminate a vast area for decades, and could potentially result in tens of thousands of deaths and billions of dollars in damage if the accident occurred at a reactor located near a large population center.[50]

That the impacts from a major accident at a commercial reactor or spent fuel pool could be very severe is no longer in debate. However, the likelihood that such accidents might occur remains a highly contentious issue. This is a particularly important area of debate since what is most relevant is not just the consequences of a nuclear accident, but what the risks of nuclear power are. Estimates for the likelihood of an accident occurring have significant uncertainties that greatly complicate projections about the safety of an expanded use of nuclear power. Despite the many uncertainties that can have a large effect on the projected risks, the authors of the MIT report admit that

> Our study has not been able to address each aspect of concern as thoroughly as deserved. One example is safety of nuclear operations. **Accordingly, we report here views of our group that we believe to be sound but that are not supported by adequate analysis.**[51]

This statement is rather shocking given the importance of reactor safety to the viability of a nuclear revival.

The probabilistic risk assessments (PRA) used to model the likelihood of accidents in high reliability systems have numerous methodological weaknesses that limit the usefulness of their results. The questions of completeness and how to incorporate design defects are particularly difficult to handle within the PRA methodology in that they essentially require the analysts to know what they don't know about what could go wrong. If important accident scenarios could be foreseen they would already be included in the analysis, and if design defects were identified they could be addressed. Adding to the difficulty of accessing reactor safety, the nuclear plants that have been built so far in the U.S. consist of 80 different designs which were built by four different reactor vendors.[52] As summarized by Edward Hagen, a development specialist at Oak Ridge National Laboratory and editor of the Control and Instrumentation section of the journal *Nuclear Safety*,

> No reactor system has ever failed because of a deficiency that could be seen on a designer's flow sheet or an analyst's model. Such deficiencies have been revealed only via operating experiences.[53]

This is a particular concern for the safety of new reactor designs that so far exist only on paper or which have only a limited amount of operating experience. Many important unforeseen accident scenarios and design flaws have been discovered during the nearly 3,000 reactor years of operating experience that have been gained at current reactors. Placing too much faith in theoretical estimates for the safety of new designs without a suitable consideration of the uncertainties involved could be a potentially catastrophic mistake.

A further limitation of the PRA methodology is that it assumes that the plants are always operating as designed. However, the GAO noted that, as of the late-1990s, "some utilities do not have current and accurate design information for their nuclear power plants."[54] The omission of design defects adds to concerns over the completeness of accident analyses. In a PRA, the accident scenarios are assumed to flow linearly from one failure to the next. In other words, it is assumed that the system as designed and built functions properly, and that it is only when equipment breaks or an operator makes a mistake that an accident can occur. However, in a real system, equipment may function as designed, but simply not be appropriate to the task, such as a pump that activates as planned, but is of insufficient power to force water to where it is needed.

Additional concerns arise due to the fact that nuclear power demands an extremely high level of competence at all times from all levels of the organization -- from the regulators and managers all the way through to the operators and maintenance crews. If the human element of the system falters, then there is the possibility for a severe accident to occur. As summarized by Edward Hagen,

> There is not now and never will be a "typical" or "average" human being whose performance and reactions to any operating condition, let alone an abnormal operating condition, can be cataloged, qualitatively defined, or quantitatively determined. There are no human robots.[55]

Finally, the increased use of computers and digital systems create important safety tradeoffs with improvements possible during normal operation, but with the potential for unexpected problems to arise during accidents. The National Research Council has noted that there remains an ongoing "controversy within the software engineering community as to whether an accurate failure probability can be assessed for software or even whether software fails randomly."[56] This controversy has led to an inconsistent treatment of software failure modes in the PRAs for nuclear plants. For example, General Electric's new Advanced Boiling Water Reactor design did not include any possibility of software failures in its risk assessment. In addition, the guidelines for performing PRAs contained in the Electric Power Research Institute's Utility Requirements Document did not include any discussion of how to incorporate software failures.[57] On the other hand, Westinghouse chose to include a subjective estimate for software unavailability in its analysis of the AP600 pressurized water reactor's protection and monitoring system.[58]

In light of the uncertainties inherent in quantitative risk assessments and the influence that may be exerted by the choices made in conducting the analysis, William Ruckelshaus, the head of the U.S. Environmental Protection Agency under both Presidents Nixon and Reagan cautioned that

> We should remember that risk assessment data can be like the captured spy: if you torture it long enough, it will tell you anything you want to know.[59]

Using historical experience with light-water reactors in the United States as a more reliable starting point for considering the risks of nuclear power, we find an unacceptably high risk of accidents under either the global or steady-state growth scenarios. As noted by the authors of the MIT study

> With regard to implementation of the global growth scenario during the period 2005-2055, both the historical and the PRA data show an unacceptable accident frequency. The expected number of core damage accidents during the scenario with current technology would be 4 [using the PRA estimates]. We believe that the number of accidents expected during this period should be 1 or less, which would be comparable with the safety of the current world LWR fleet. A larger number poses potential significant public health risks and, as already noted, would destroy public confidence.[60]

In the 2,745 total reactor-years of experience accumulated at commercial plants there has been one loss of coolant accident that has resulted in a partial core meltdown as well as a number of near misses and close calls. Assuming for simplicity that the failure rate remains constant, we estimated that the probability of a TMI level accident occurring at a currently operating reactor is between 1 in 8,440 and 1 in 630 per year.[61] Using the median accident rate, and retaining the assumption from the MIT report that future plants will be ten times safer than those in operation today, we find that the probability of at least one TMI level accident occurring somewhere in the world by 2030 would be roughly 45 percent under the global growth scenario and more than 50 percent under the steady-state growth scenario. By 2050, the probability of at least one such accident having occurred would be greater than 75 percent for the global growth scenario and over 90 percent for the steady-state growth scenario. In fact, for 2,500 reactors online in 2050, there would be nearly *a 50-50 chance* that three or more accidents will have occurred around the world by mid-century.

In addition to accidents, a successful terrorist attack on the scale of those carried out on September 11, 2001, could also lead to a major release of radiation. While the likelihood of this kind of attack occurring is small, more reactors mean more targets, and we should not forget that the probability of the World Trade Center towers collapsing due to the impact of civilian aircraft was also considered to be small before they fell. Already at least once since September 11 the Federal Aviation Administration has issued an order temporarily banning all general aviation flying within 10 nautical miles (11.5 miles) of 86 nuclear power and nuclear weapons production sites due to the threat of terrorist actions.[62]

The history of public opposition to nuclear power clearly demonstrates the importance of reactor safety to the acceptability of this technology. In light of the high probabilities that at least one meltdown would occur somewhere in the world between now and 2050, the possibility that public opinion could turn sharply against the widespread use of nuclear power following such an accident is a significant vulnerability with plans that envision a heavy reliance on this energy source. If nuclear power is in the process of being expanded and accounts for a significant amount of overall electricity production, then public pressure to shutdown existing plants would leave open far fewer energy options (particularly in terms of reducing greenhouse emissions). The options that would then be available to achieve a rapid phase out of nuclear power would likely come at a very high price, considering both the sunken capital in the completed nuclear plants and the cost of ad hoc measures that would be needed to rapidly replace the off-lined nuclear capacity. On the other hand, if long-term plans to phase out nuclear power were already being carried out when an accident or attack occurred, there would be far more options available and those options could be accelerated with far less disruption to the overall economy.

Section S.5 – The Legacy of Nuclear Waste

Finally, the difficulty of managing the radioactive wastes generated by the nuclear fuel cycle is one of a longest standing challenges accompanying the use of nuclear power. In addition to its long half-life and its high radiotoxicity, the existence of large quantities of weapons usable plutonium in the spent fuel from commercial power plants complicates the waste management problem by raising concerns over nuclear weapons proliferation.[63] This link between nuclear waste and nuclear weapons makes reprocessing technologies highly undesirable, even if they could somehow be made economical and could overcome their significant environmental problems. Finally, it is important to note that the impacts of nuclear waste have so far fallen disproportionately on Indigenous Peoples in the United States and around the world, which raises serious concerns about environmental justice.[64]

The radioactive wastes generated by the nuclear fuel cycle span a very wide range of volumes and hazards. While the vast majority of the radioactivity is in spent fuel and reprocessing wastes, the vast majority of the volume is in uranium mine and mill tailings and so-called low-level wastes. Unlike the management of high-level waste, which is a federal responsibility, the disposal of low-level waste is the responsibility of individual states. The development of low-level waste disposal sites has encountered a number of problems and several facilities have either been denied a license or have been otherwise abandoned. Of particular concern is the need to dispose of the large volumes of depleted uranium that are generated by enrichment plants. The disposal of depleted uranium poses long-term radiological hazards similar to the disposal of some types of transuranic wastes, and will likely require the development of a repository comparable to the Waste Isolation Pilot Plant in New Mexico.

While the management of low-level waste will continue to pose a challenge in the future, by far the largest concern regarding radioactive waste management is how to handle the spent nuclear fuel. Greatly complicating this task are the very long half-lives of some of the radionuclides present in this waste (for example plutonium-239 – half-life of 24,000 years, technetium-99 – half-life of 212,000 years, cesium-135 – half-life of 2.3 million years, and iodine-129 – half-life of 15.7 million years). In addition, the spent fuel presents security risks due to the fact that it contains weapons useable plutonium that can be chemically separated by reprocessing. The current fleet of U.S. reactors discharges approximately 22 metric tons per GW per year. By the end of 2005 there was already an estimated 53,100 metric tons of commercial spent fuel stored at 76 sites in 33 states around the U.S. Nearly 90 percent of the spent fuel was stored in cooling pools, while the remainder was stored in independent spent fuel storage installations, mostly dry casks located at reactor sites.[65] By 2012, which is the very earliest date that the Yucca Mountain repository could possibly be opened, the amount of spent fuel discharged from the existing fleet of reactors will amount to more than 67,500 MT. Thus, even without any new nuclear construction, by 2012 the inventory of commercial spent fuel in the U.S. would already exceed the 63,000 MT statutory limit for Yucca Mountain.

Through 2050, the proposed expansion of nuclear power under the global growth scenario would lead to nearly a doubling of the average rate at which spent fuel is currently generated with proportionally larger increases under the steady-state growth scenario. Assuming a constant growth rate for nuclear power, and that Yucca Mountain itself was successfully licensed and built, a new repository with the capacity of Yucca Mountain would have to come online somewhere in the world every <u>six years</u> in order to handle the amount of waste that would be generated under the global growth scenario. For the steady-state growth scenario a new Yucca Mountain sized repository would need to be opened every <u>three years</u> on average just to keep up with the waste being generated.[66]

The characterization and siting of repositories rapidly enough to handle the volumes of waste that would be generated by a nuclear revival would be a very serious challenge. The site of the Yucca Mountain repository has been studied for more than two decades, and it has been the sole focus of the Department of Energy since 1987. However, despite this effort and nearly $9 billion in expenditures, as yet no license application has been filed and a key element of the regulations governing the site has been struck down by the courts and re-issued in draft form. Adding to the uncertainty about the repository's future is the fact that the draft standard proposed by the EPA in August 2005 would be the least protective by far of any repository regulation anywhere in the world, and will therefore likely face future challenges.[67]

As a result of their failure to meet the Congressionally mandated deadline of January 31, 1998, for beginning to accept spent fuel from the utilities, the DOE has been sued by the utilities to recover costs associated with the storage of waste on site. The courts have so far found the DOE specifically liable for fuel storage costs at three permanently closed reactors. The total amount of this liability has yet to be agreed upon due, in part, to the fact that the date when the fuel might finally be accepted by the DOE remains speculative. As acknowledged in January 2006 by Ernest Moniz and John Deutch, the two co-chairs of the MIT study, "it is unclear whether Yucca Mountain will ever receive a license from the Nuclear Regulatory Commission."[68] In fact, in February 2006, Secretary of Energy Samuel Bodman admitted that the Department of Energy can no longer make an official estimate for when the Yucca Mountain repository might open due to ongoing difficulties faced by the project.[69] Internationally, no country currently plans to have a repository in operation before 2020 at the very earliest, and all repository programs have encountered problems.

Due to the complexity of the problem and the very long times to be considered, predictions of the ability for a repository to contain radioactivity have a significant degree of uncertainty. Similar to the issues of completeness in the context of probabilistic risk assessments, the completeness of the conceptual models used to simulate the behavior of a repository presents a particular challenge in that it requires the designers to know what they don't know about the geologic and chemical processes that will be important at a given site. As summarized by the National Research Council,

> Simply stated, a transport model is only as good as the conceptualizations of the properties and processes that govern radionuclide transport on which it is based. If the model does not properly account for the physical, hydrogeochemical, and when appropriate, biological processes and system properties that actually control radionuclide migration in both the near- and far-fields of the repository, then model-derived estimates of radionuclide transport are very likely to have very large -- even orders of magnitude -- systematic errors.[70]

Unfortunately, the history of past waste management programs reveal a number of cases that demonstrate the dangers inherent in relying on incomplete physical models for decision making.

When many of the sites within the U.S. nuclear weapons complex were founded, it was believed that their arid climates and thick unsaturated zones would protect the groundwater for hundreds to thousands of years. Measurements over time, however, revealed these early assumptions to be substantially in error. For example, the travel time estimated by the DOE for contaminants to reach the Snake River aquifer under the Idaho National Laboratory has fallen from tens of thousands of years in their predictions from the mid-1960s to just a few tens of years in their predictions today. Other examples of the failure of conceptual models include the discovery of (1) rapid tritium migration at the waste disposal facility at Beatty, Nevada, (2) the mobility of radionuclides below the high-level waste tanks at Hanford, Washington, and (3) the colloid mediated transport of plutonium from nuclear weapons tests at the Nevada Test Site.[71]

Similar surprises have occurred at Yucca Mountain as well. For example, chlorine-36, a radionuclide distributed around the globe as a result of nuclear weapons tests in the Pacific Ocean, was found in some of the water samples collected at the repository depth from experimental tunnels at Yucca Mountain. This finding implied that there were "fast" water pathways which had allowed water to migrate from the surface down to the level of the repository in as little as 40 to 50 years rather than the hundreds to thousands of years previously assumed by DOE.[72] Thus, what was supposed to be a "dry" repository, was instead found to be potentially far wetter.

Adding to the uncertainty in predictions of repository performance are future changes to the climate and to human land use patterns and lifestyles. Over the next few hundred thousand years, the Earth's climate will go through a number of natural variations while new climate states may emerge as a result of the buildup of greenhouse gases. With respect to the magnitude of possible changes in human behavior, one has only to recall that less than 600 years ago no Europeans were living in permanent colonies on the American continents, that as little as 12,000 years ago no society practiced widespread agriculture or raised herds of domesticated animals for food, and that approximately 30,000 years ago Neanderthals could still be found living in isolated pockets across Europe and western Asia. In order to try and address these kinds of unknowns, it is necessary for strict standards to be set for a repository, and for those standards to focus on conservative scenarios for future human activities. As such, it is helpful to place a strong focus on robust exposure pathways such as drinking water which are unlikely to change significantly even over very long times. It is, therefore, particularly problematic that the EPA has attempted to relax the Safe Drinking Water Act standards at Yucca Mountain. These proposed relaxations include allowing the DOE to evaluate the impact on groundwater during the first 10,000 years at a point as much as 18 kilometers away from the repository boundary and removing all specific drinking water standards for times beyond 10,000 years.

Even if the U.S. repository program had not been plagued by delays and poor management, a number of serious concerns would remain. First, the land upon which the Nevada Test Site and Yucca Mountain are located is claimed by the Western Shoshone Nation which opposes the placement of the repository. The lack of informed consent from those with a deep cultural and historical connection to the land should alone be sufficient to prevent any further consideration of the site. Second, Yucca Mountain is a highly complex site which is geologically unique in many important ways from any other locations being considered around the world. Yucca Mountain is the only site proposed for construction in an oxidizing environment, which significantly increases the rate of waste corrosion and contaminant transport compared to sites with a reducing environment. Third, the DOE itself projects that Yucca Mountain would not be able to meet the most basic requirement of a repository, namely that it should maintain the peak dose to an acceptably low level. While IEER shares the scientific consensus that mined repository disposal is the least worst option available for the existing spent fuel and high-level waste, it is our conclusion that Yucca Mountain cannot be regarded as an appropriate site for the development of such a repository, and that the search for an alternative location with a more appropriate geology should begin as soon as possible.

Alternatives to disposal in a mined repository are unlikely to overcome the many challenges posed by the amount of waste that would be generated under either the global or steady-state growth scenarios. Proposals to reprocess the spent fuel would not only <u>not</u> solve the waste problem, but would greatly increase the vulnerabilities of a nuclear revival. Reprocessing schemes are expensive and create a number of serious environmental risks. Routine discharges and accidents at existing commercial and military reprocessing facilities have contaminated large areas in the United States, Russia, the English Channel, and the Irish sea. The 1957 explosion of a waste tank at the Chelyabinsk-65 military reprocessing plant in the Soviet Union contaminated an area larger than the state of Connecticut and led to the evacuation of more than 10,000 people.[73] Similar explosions in the high-level waste tanks at Hanford or the Savannah River Site are also possible if they were to lose cooling.[74] In addition, reprocessing generates a large amount of waste that would still require geologic disposal. Vitrified high-level waste and spent MOX fuel both require a repository similar to that required for unreprocessed spent fuel. As with the depleted uranium, the unfissioned uranium separated by reprocessing would eventually have to be disposed of in a repository similar to the Waste Isolation Pilot Plant in New Mexico. The amounts of plutonium bearing wastes generated during the decommissioning of the reprocessing plants are also expected to be quite large and to add significantly to the volume of waste destined for repository disposal. Finally, and most importantly, reprocessing results in the separation of plutonium that can be used to make nuclear weapons. While future reprocessing technologies like UREX+ or pyroprocessing, if successfully developed and eventually commercialized, could have some nonproliferation benefits, they would still pose a significant risk if deployed on a large scale.

The authors of the MIT study acknowledge the high cost as well as the negative health, environmental, and security impacts of reprocessing and, as such, advocate against its use. Instead they propose interim storage and expanded research on deep borehole disposal. While it is possible that deep boreholes might prove to be an acceptable alternative to mined repositories in countries which have a smaller amount of waste to manage, this cannot yet be determined. As summarized by the U.K. waste management agency, Nirex, in 2004 “no practical demonstration of the application of this concept has taken place” and “[i]t is also likely that considerable sums of money would be required before it could be brought up to the same level of understanding that already exists for the several different types of mined geological disposal concept[s] that are currently proposed by waste disposal organisations world-wide.”[75] Committing to a large increase in the rate of waste generation based only on the potential plausibility of a future waste management option would be to repeat the central error of nuclear power’s past. The concept for mined geologic repositories dates back to at least 1957, but turning this idea into a reality has proven quite difficult, and a solution to the waste problem remains elusive to this date.

Irrespective of future nuclear power development, there will have to be a long-term effort to manage the waste that is already stored around the world, and that which will continue to be generated by the existing fleet of reactors. A solution to this problem cannot simply be to transfer the liability of spent fuel from the private utilities to the federal government as a means of allowing new plants to be built. This does nothing to resolve the risks to society posed by this very hazardous and long-lived material. To manage this waste IEER proposes that the existing spent fuel be removed from the cooling pools as soon as possible and placed into hardened onsite storage (HOSS). This strategy would consist of first placing the spent fuel into dry casks which include an outer shell of Alloy-22, the corrosion resistant alloy proposed for use in the U.S. repository. This strategy would allow greater experience to be gained with this relatively new material, and to allow longer-term measurements of its properties to be made. All spent fuel older than five year should be removed from the cooling pools and stored in these types of dry casks. The casks should then be placed into hardened or underground structures onsite that would reduce the chance of a terrorist attack successfully damaging the casks and mitigate the impacts of any release of radioactivity. This strategy would substantially reduce the risks posed by the storage of spent fuel in densely packed cooling pools, and allow sufficient time for a more sound repository program to be pursued. As a result of its performance on Yucca Mountain and other projects, it is our conclusion that the DOE is not the right agency to manage such a program. A new, highly transparent agency with strict public oversight and no institutional conflict of interest concerning the promotion of new reactors should be created to manage the existing commercial spent fuel.

While the risks posed by nuclear waste must be compared to the potentially catastrophic impacts of global climate change, significantly expanding the production of highly radioactive, long-lived waste which also contains weapons usable plutonium at a time when not one spent fuel rod has been permanently disposed of anywhere in the world, is not a sound decision. The future production of spent fuel should be minimized to the maximum extent practicable, and the existing waste should be managed as we have recommended above.

Section S.6 - Stabilizing the Climate

As our analysis has shown, nuclear power is a uniquely dangerous source of electricity that would create a number of serious health, environmental, and security risks if employed on a large scale. In addition, we have also found that it is likely to be an expensive source of electricity with costs in the range of six to seven cents per kWh for new reactors. In considering other options that may be available, we have found that there are a number of alternatives for achieving significant reductions in CO_2 emissions that were either ready for immediate implementation or were very likely to be commercialized within the next five to fifteen years. Most importantly, we found that when projected over this same timeframe, the cost of each of these options also tended to fall roughly within or below the range of six to seven cents per kWh.[76] Thus, the question of cost becomes less important in choosing between the available alternatives, and the deciding factors instead hinge on the rapidity with which the options can be brought online and on their relative environmental impacts.

Of the alternatives available in the near-term, the two most promising options are efforts to increase the efficiency of electricity generation and use and a large-scale expansion of wind power at favorable sites. Improvements in efficiency as well as a reduction in demand through conservation have the potential for significant benefits throughout the Global North and to enable countries in the Global South to leapfrog over older, dirtier technologies. Unlike programs focused on simply increasing supply, demand side options can result in low or negative cost reductions in greenhouse gas emissions while simultaneously providing new jobs and opening new avenues for economic growth. Combined with these efforts, the expanded use of renewable energy, particularly wind power, offers the most economically attractive option for supplying the required near-term incremental growth in generating capacity. At approximately four to six cents per kWh, wind power at favorable sites is already competitive with natural gas or new nuclear power. With the proper priorities on investment in transmission and distribution infrastructure and changes to the ways in which the electricity sector is regulated, wind power could rapidly make a significant contribution. In fact, without any major changes to the existing grid, wind power could expand in the near term to make up 15 to 20 percent of the U.S. electricity supply as compared to less than one-half of one percent today. This expansion could be achieved without having any negative impacts on the overall stability or reliability of the transmission grid. Similar potential for these alternatives exist throughout the Global North. As summarized by the British Department of Trade and Industry

> Energy efficiency is likely to be the cheapest and safest way of addressing all four objectives [i.e. a reduction of greenhouse gas emissions, the maintenance of a reliable energy supply, promotion of competitive markets, and an assurance of adequate and affordable heat to every home]. Renewable energy will also play an important part in reducing carbon emissions, while also strengthening energy security and improving our industrial competitiveness as we develop cleaner technologies, products, and processes.[77]

While it will require a significant effort to achieve the widespread implementation of new efficiency programs and to develop the necessary infrastructure to support a large increase in the contribution of wind power, it is important to compare those efforts to the difficulties that would be encountered in restarting a nuclear power industry that last hasn't had a new order placed in the U.S. in more than 25 years and hasn't opened a single new plant built in the last ten years.[78] Including interest payments on debt, each new nuclear plant is expected to cost nearly $2.6 billion to build under the MIT base case assumptions, and dozens of such plants would have to be started in the next five to fifteen years in order to remain on track to meet the global growth or steady-state growth scenarios.[79] In addition, we note that the current fossil fuel based energy system is also very expensive to maintain. For example, the International Energy Agency estimates that the amount of investment in oil and gas between 2001 and 2030 will total nearly $6.1 trillion, with 72 percent of that investment going towards new exploration and development efforts.[80] Finally, unlike the decision to build new nuclear power plants, it is important to recognize that there is already strong and sustained public support for programs to expand energy efficiency efforts and to expand the use of renewable resources which would help to facilitate their rapid implementation.

While many improvements can be made in the near term, a significant potential will continue to exist for increasing energy efficiency throughout this half century. For example, as the current building stock turns over, older, less efficient buildings can be replaced by buildings that incorporate advanced features such as passive solar systems for lighting and water heating, greatly improved insulation, and high efficiency heating and cooling systems such as earth source heat pumps. In addition to the replacement of buildings, the IPCC has identified what it calls "robust policies" for reducing greenhouse gas emissions over the longer term that include "social efficiency improvements such as public transport introduction, dematerialization promoted by lifestyle changes and the introduction of recycling systems."[81] As recommended by Dr. Arjun Makhijani in 2001

> Public transportation in urban areas should be regarded as a utility, much like water, electricity or telephones. A diverse system of transport that includes cars, motorized and rail public transport, bicycle lanes and sidewalks would reduce vulnerabilities to terrorism by diversifying the modes by which people could travel in cities. By making public transportation safe, efficient, economical, frequent, and convenient, energy use as well as time for commuting could be greatly reduced with all the attendant social, economic, and environmental benefits.[82]

In addition, to continuing improvements in energy efficiency the utilization of wind power, thin-film solar cells, advanced hydropower, and some types of sustainable biomass could allow renewables to make up an increasingly significant proportion of the electricity supply over the medium-term. This expansion could be facilitated through the development of a robust mix of technologies that have different types of intermittency and variability, the development of strengthened regional grids to help stabilize the contribution of wind and solar power through geographic distribution, the use of pumped hydropower systems to store excess electricity during times of low demand, and the tighter integration of large scale wind farms with natural gas fired capacity. Beyond its potential contribution in the Global North, the development of cost effective solar power could also have a profound impact on the development of electricity systems in the Global South where there is a lack of robust transmission and distribution infrastructures in many areas.

The continued expansion of both efficiency efforts and of renewable energy have few negative environmental or security impacts compared our present energy system and, in fact, have many important advantages. As a result, these options should be pursued to the very maximum extent possible. However, in order to stabilize the climate by mid-century, it appears likely that some transition technologies which have more significant health and environmental tradeoffs will also be needed over the coming decades. In much the same way that a cancer patient may choose to undergo chemotherapy despite its toxic side effects in order to help fight off a cancer, we will have to make a number of difficult choices in order to avoid the potentially catastrophic consequences of not dramatically reducing carbon emissions by mid-century while simultaneously allowing the Global South to greatly expand their use of electricity.[83] In this vein, two of the most important transition strategies available are likely to be an increased reliance on the use of liquefied natural gas (LNG) and the use of integrated coal gasification plants with sequestration of carbon in geologic formations.

Compared to pulverized coal plants, combined cycle natural gas plants emits about 55 percent less CO_2 for the same amount of generation.[84] If efficiency improvements to the energy system as a whole and an expanded liquidification and regasification infrastructure can stabilize the long-term price of natural gas at the cost of imported LNG, then the use of combined cycle generating plants is likely to remain an economically reasonable choice for replacing some of the highly inefficient coal fired plants in operation today. For example, the levelized gas prices in the moderate to high price scenarios from the MIT study ($4.42 to $6.72 per million BTU over 40 years) are consistent with the recent average import price of LNG in the United States ($4.37 per MMBtu between 2000 and 2004), the average price for LNG imports to Japan and South Korea over the past decade (~$4 per MMBtu), and the expected price for future LNG imports to India ($4.10 per MMBtu).[85]

With respect to coal, the use of gasification technologies would greatly reduce the emissions of mercury, particulates, and sulfur and nitrogen oxides. In addition, the higher efficiency of IGCC plants compared to pulverized coal plants would also reduce, somewhat, the carbon emissions from these newer plants. However, for coal to be considered as a potential transition technology, it must be accompanied by carbon sequestration. Experience in the U.S. with carbon dioxide injection into oil fields to enhance the recovery of petroleum has been gained since at least 1972. Overall, about 43 million tons per year of carbon dioxide is currently being injected each year at 65 enhanced oil recovery programs in the United States alone.[86] A related source of experience has been gained through the sequestration of acid gas from natural gas production in depleted gas fields and nearby saline aquifers.

To date, one of the most important demonstrations of carbon sequestration has been the Sleipner gas fields in the North Sea. Motivated by the imposition of a tax on carbon emissions, the Norwegian company Statoil began injecting CO_2 into a sandstone formation under the sea floor in the mid-1990s. A similar CO_2 sequestration program began in April 2004 at the In Salah natural gas fields in Algeria. Additional projects are currently being planned by Statoil in the Barents Sea and by Chevron at Barrow Island off the western coast of Australia.[87] Based on assessments made over the last ten years, it appears likely that carbon sequestration in geologic formations would have a significant potential for reducing greenhouse gas emissions over the next several decades. While the costs of such strategies are more uncertain than those of other mitigation options, our central estimates for the cost of electricity from natural gas or gasified coal plants with carbon sequestration still fall within the range of six to seven cents we have found for other options.

Some of the most troubling aspects of these transition technologies, such as mountain top removal mining for coal, would be mitigated by the reduction in demand that would be achieved through an increase in efficiency and the rapid expansion of alternative energy sources. In addition, it appears quite likely that coal gasification and carbon sequestration would be better suited to the Western United States where mine mouth coal could be used given the greater access to oil and gas fields which have already been explored and which offer the potential for added economic benefits from enhanced oil and gas recovery. On the other hand, the Eastern U.S., where mountain top removal mining is currently practiced, would appear better suited for an expanded use of liquefied natural gas as a transition strategy given the existing regasification capacity, the well developed gas distribution system, and the shorter transportation distances from the Caribbean, Venezuela, and Western Africa.

While the continued use of fossil fuels during the transition period will have many serious drawbacks, these must be weighed against the potentially catastrophic damage that could result from global climate change and against the uniquely serious risks that accompany the use of nuclear power, such as the potential for nuclear weapons proliferation and the risks of catastrophic reactor accidents, and the difficulties of safely managing long-lived radioactive waste. Proposals for a revival of nuclear power and its widespread use over the coming decades, would take the already deeply complicated problem of how to reduce global greenhouse gas emissions while expanding access to electricity in the Global South and make it even more difficult to deal with. Trading one uncertain, but potentially catastrophic health, environmental, and security threat for another is not a sensible basis for an energy policy.

Just as the claim that nuclear power would one day be “too cheap to meter” was known to be a myth well before ground was broken on the first civilian reactor in the United States, and the link between the nuclear fuel cycle and the potential to manufacture nuclear weapons was widely acknowledged before President Eisenhower first voiced his vision for the “Atoms-for-Peace” program, a careful examination today reveals that the expense and unique vulnerabilities associated with nuclear power would make it a very risky, unsustainable, and uncertain option for reducing greenhouse gas emissions. As the authors of the MIT report themselves conclude

> The potential impact on the public from safety or waste management failure and the link to nuclear explosives technology are unique to nuclear energy among energy supply options. **These characteristics and the fact that nuclear is more costly, make it impossible today to make a credible case for the immediate expanded use of nuclear power.**[88]

It is very unlikely that these problems can be successfully overcome given the large number of reactors that would be required if nuclear power were to play a significant role in reducing greenhouse gas emissions if we are to avoid the more serious consequences of global climate change. This is particularly true given the urgent need to begin reducing emissions as soon as possible. It has now been more than 50 years since the birth of the civilian nuclear power industry and more than 25 years since the last reactor order was placed in the United States. It is time for the global community to move on from a belief in the nuclear option and to begin focusing its efforts on developing more rapid, more robust, and more sustainable options for addressing the most pressing environmental concern of our day. The alternatives are available if we have the will to make them a reality. If not, it will be our-children and our grand children who will have to live with the consequences of our failure.

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Endnotes

[1] Millennium Assessment 2005 p. 17
[2] MIT 2003 p. 22 (emphasis added)
[3] IPCC 2001f p. 7,12 and IPCC 2001d p. 527
[4] IPCC 2001i p. 958-959
[5] IPCC 2002 p. 24
[6] IPCC 2002 p. 22
[7] Millennium Assessment 2005 p. 17
[8] ACIA 2004 p. 58
[9] Portner, Langenbuch, and Reipschlager 2004 p. 705 and 711, Ishimatsu et al. 2004 p. 731 and 737-739, and Kurihara, Shimode, and Shirayama 2004 p. 743-744 and 746-748
[10] Royal Society 2005 p. 23
[11] IPCC 2001g p. 453
[12] WHO 2003 p. 7, 17, and 19
[13] See for example Broecker 1997, Stocker and Schmittner 1997, Rahmstorf and Ganopolski 1999, Rahmstorf 2000, and Rahmstorf and Zickfeld 2005
[14] NAS/NRC 2002 p. 1
[15] Meier 2002 p. i-iii and 25-27
[16] MIT 2003 p. 1
[17] In the year 2000, the total amount of electricity generated by nuclear power was 2,230 billion kWh. This is equivalent to the electricity that would be produced by approximately 300 GW of nuclear power operating at an 85 percent capacity factor. [MIT 2003 p. 115]
[18] MIT 2003 p. 26
[19] [MIT 2003 p. 115]. The rate of electricity growth assumed in the MIT analysis is well below the 3.8 percent average annual growth rate in electricity consumption experienced between 1971 and 2000. A more rapid growth in electricity demand would lead to an even greater number of nuclear reactors being required. [IEA 2002 p. 411]
[20] The information about current levels of generation and about the relative levels of CO_2 emissions per kWh used in this calculation were taken from [IEA 2002 p. 411 and 413 and MIT 2003 p. 3 and 115]
[21] MIT 2003 p. 115
[22] MIT 2003 p. 115 and EIA 2004e p. 224
[23] A number of alternate visions have been proposed for how to reduce greenhouse gas emissions and simultaneously phase out nuclear power. See for example: *Energy Innovations* from the Alliance to Save Energy, American Council for an Energy-Efficient Economy, Natural Resources Defense Council, the Tellus Institute, and the Union of Concerned Scientists [ASE et al. 1997], *Securing the Energy Future of the United States* from the Institute for Energy and Environmental Research [Makhijani 2001b], and the *Clean Energy Blueprint* from the Union of Concerned Scientists [Clemmer et al. 2001]. While the significant increase in the projected long-term price of oil and natural gas, the recent advances in lower cost thin-film solar cell technology, and the experience that has been gained with carbon sequestration projects make some of the conclusions in these analyses out of date, they continue to provide many valuable insights into how the energy system could evolve and improve over the coming decades to address climate change without the construction of new nuclear power plants. For a more recent analysis showing how even a country as reliant on nuclear power as France could reduce emissions and phase out nuclear power see *Low-Carbon Diet without Nukes in France* from the Institute for Energy and Environmental Research [Makhijani and Makhijani 2006b].
[24] NRC 2005 p. 135
[25] Strauss 1954
[26] NAS/NRC 1992 p. 31
[27] Forbes 1985
[28] MIT 2003 p. 40 and 42-43
[29] EIA 2006 p. 65 and 67
[30] Given the poor economics of nuclear power, a number of large new subsidies have been proposed to help prop up the industry. The authors of the MIT study favor a government subsidy of $4.85 billion over the next 10 years for a variety of "analysis, research, development, and demonstration" programs. In addition the authors proposed a $200 million per plant production credit to be given to the first 10 new plants to be built. [MIT 2003 p. 8, 13-16, and 94] The Energy Policy Act of 2005 contains even larger subsidies. The law allows the DOE to offer loan guarantees

that the Congressional Budget Office estimates could carry a subsidy value of up to $600 million per plant. In addition, the law authorizes up to $1 billion in production tax credits that can be offered to each of the first six new plants. Finally, the DOE can offer insurance against regulatory delays totaling up to $500 million per plant for the first two new plants and up to $250 million for next four. [U.S. Congress 2005 Sections 638, 1306, 1702, and 1703] An additional $650 million in federal subsidies not included in the Energy Policy Act has been requested by two utility consortiums to help pay for preparing the paperwork associated with submitting combined construction and operating licenses. [Holt 2005b p. CRS-3 to CRS-5]

[31] MIT 2003 p. 40-41 (emphasis added)

[32] The Committee on Atomic Energy was commissioned in 1946 by then Under-Secretary of State Dean Acheson. The committee was chaired by David Lilienthal, then the Chairman of the Tennessee Valley Authority and later the first Chairman of the Atomic Energy Commission. The committee also included the presidents of the New Jersey Bell Telephone Company, Monsanto, and General Electric, as well as Robert Oppenheimer who had headed the bomb design work at Los Alamos Laboratory during the Manhattan Project. [Acheson and Lilienthal 1946 p. 4]

[33] MIT 2003 p. 12

[34] A typical 1000 MW light-water nuclear power plant requires approximately 100 to 120 metric tons separative work units (MTSWU) per year in enrichment services to provide its fuel. For simplicity in this calculation we have assumed 110 MTSWU per year would be required for future reactors. However, the increased demand for uranium under the global or steady-state growth scenario would make the higher enrichment levels more likely since the amount of uranium feed material and the amount of enrichment services needed are inversely related for a fixed percentage of U-235 in the tails. The assumptions made in the MIT report are consistent with this conclusion. In that report the authors assume the equivalent of nearly 125 MTSWU per year of enrichment services will be required for each reactor. [MIT 2003 p. 30 and 145-146]

[35] ElBaradei 2004c

[36] For simplicity this calculation assumes 110 MTSWU per year of enrichment services are required for each 1000 MW reactor and that 25 kilograms of HEU is required per warhead.

[37] DOE 1996 p. 25 and NAS/NRC 2002b p. 40

[38] Sokolski 2005 p. 25

[39] as quoted in [Makhijani 1998 p. 14]

[40] ElBaradei 2004

[41] For an analysis of the legal obligation of the five nuclear weapons states to bring to a conclusion negotiations on disarmament under the Nuclear Nonproliferation Treaty see [Deller, Makhijani, and Burroughs 2003 p. 19-40]

[42] New York Times 2004

[43] GAO 1986, Riccio 2001, and U.S. Congress 2005 Sections 601-610

[44] Perrow 1999 p. 355-360

[45] New York Times 2005d

[46] Weinberg 1994 p. 133-134

[47] Feynman 1988 p. 223

[48] For a further discussion see [Lochbaum 2000].

[49] Meserve 2002

[50] Alvarez 2002 and Alvarez et al. 2003 p. 7, 10, and 39-40

[51] MIT 2003 p. 85 (emphasis added)

[52] NRC 2005 p. 38

[53] Hagen 1980 p. 189-191

[54] GAO 1999 p. 2

[55] Hagen 1980 p. 191

[56] NAS/NRC 1997 p. 7

[57] NAS/NRC 1997 p. 55

[58] NAS/NRC 1997 p. 55

[59] Ruckelshaus 1984 p. 157-158

[60] MIT 2003 p. 48

[61] Assuming that accidents at nuclear plants occur randomly, we can calculate the probability of having seen less than two accidents over approximately 3,000 hours of operation for different assumptions about the underlying accident rate. The cited range represents our estimate for the 5-95 percent confidence interval for the average accident rate (i.e. there is a 5 percent chance that the actual accident rate is greater than 1 in 633 per year and a 5 percent

chance that it is less than 1 in 8,440 per year.) The median accident rate (i.e., the value for which half of the estimates are above and half are below) is approximately 1 in 1,800 per year.
[62] FAA 2001
[63] At a burnup of 50 gigawatt-days (GWD) per ton, a typical 1,000 MW reactor would discharge approximately 20 metric tons of spent fuel per year containing nearly 265 kilograms of Pu-239. If chemically separated through reprocessing, this would be enough plutonium to make 33 nuclear weapons (assuming eight kilograms per bomb). [MIT 2003 p. 120]
[64] For further discussion of the impacts of uranium mining on Indigenous Peoples see for example [Brugge and Goble 2002] and Chapter 5 of *Nuclear Wastelands* [Makhijani, Hu, and Yih 2000 p. 105-168]. In the U.S., the site of the proposed Yucca Mountain repository is on land claimed by the Western Shoshone, while the Private Fuel Storage facility, that has been proposed by a consortium of nuclear utilities, is planned for construction on the land of the Skull Valley Band of Goshute Indians.
[65] Andrews 2004 p. CRS-3 and NRC 2005 p. 26
[66] Beyond 2050, if the number of reactors was held constant at 1000 GW of nuclear capacity, the rate of waste generation would be roughly three times the present level and a new repository the size of Yucca Mountain would be needed every three to four years as noted by the authors of the MIT study. [MIT 2003 p. 61] The waste problem under the steady-state growth scenario would be proportionally larger.
[67] For a further discussion of the proposed EPA Yucca Mountain standard and the IEER recommendations for a more protective regulation to govern repository development see [Makhijani and Smith 2005b].
[68] Washington Post 2006c
[69] New York Times 2006
[70] NAS/NRC 2001 p. 92
[71] NAS/NRC 2001 p. 30, 93, and 95-96 and Long and Ewing 2004 p. 381 and 391
[72] NAS/NRC 2001 p. 95-96, Macfarlane 2003 p. 789-790, Campbell et. al. 2003 p. 43, 59-60, and Long and Ewing 2004 p. 374-375
[73] Hu, Makhijani, & Yih 1992 p. 80-94
[74] Hu, Makhijani, & Yih 1992 p. 95-107
[75] Nirex 2004 p. vi
[76] The importance of the fact that the cost of all of the alternatives tend to cluster around six to seven cents per kWh was originally noted by Dr. Arjun Makhijani.
[77] DTI 2003 p. 11
[78] Dr. Arjun Makhijani has long advocated for changes to the U.S. energy system. For a discussion of the IEER recommendations put forth by Dr. Makhijani for how to best facilitate the expansion of energy efficiency programs and the development of renewable energy resources, including actions at the state and local level, see [Makhijani and Saleska 1999 p. 181-195], [Makhijani 2001b p. 48-57], and [Makhijani et al. 2004 p. 7-10]
[79] MIT 2003 p. 132
[80] IEA 2003b
[81] IPCC 2001 p. 159
[82] Makhijani 2001b p. 21
[83] The analogy of balancing the tradeoffs between the impacts of transition technologies and those of climate change to the use of chemotherapy in fighting cancer was originally put forth by Dr. Arjun Makhijani.
[84] MIT 2003 p. 3 and 42 and EIA 2004e p. 224 and 339
[85] MIT 2003 p. 43, EIA 2005 p. 3 and 97, EIA 2003d p. 35, Zaidi 2005, and Jensen 2003 p. 20 and 27
[86] Freund 2003 p. 2
[87] IPCC 2005 p. 5-9
[88] MIT 2003 p. 22 (emphasis added)