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# The Future of Nuclear Energy

Richard K. Lester

MIT-IPC-03-008

December 2003

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Over the next 50 years, unless patterns change dramatically, energy production and use will contribute to global warming through the atmospheric emission of hundreds of billions of tonnes of carbon in the form of carbon dioxide. Nuclear power could be one option for reducing carbon emissions. At present, however, this seems unlikely: in many countries nuclear power faces stagnation and decline. This paper analyzes what would be required to retain nuclear power as a significant global option for reducing greenhouse gas emissions and meeting growing needs for electricity supply.

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# The Future of Nuclear Energy

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# The Future of Nuclear Energy

Richard K. Lester

The business of making 50-year predictions about nuclear power is not for the fainthearted, but here is one that seems relatively safe: the most important commercial product of nuclear technology for the next 50 years will be a household commodity -- electricity.

In the longer run there are many other possible applications of low-energy nuclear forces and interactions, such as space propulsion, quantum computing, perhaps hydrogen production. Medical uses of nuclear technology are growing rapidly. The world of nuclear applications is still at a very early stage. We are today less than 70 years removed from the discovery of nuclear fission. In contrast, more than 170 years have passed since the discovery of electromagnetism. I invite this group to contemplate all that has happened in the field of electromagnetics over the last 100 years, and then to consider where we may be 100 years from now with respect to applications of nuclear interactions. In this regard, it is unfortunate and short-sighted that many universities have elected to shut down their nuclear engineering departments in recent years.

But for my purposes today that is a digression. For the foreseeable future, the most important commercial product will be electricity. There is, of course, nothing unique about that product. It is produced in many different ways. Moreover, one of the characteristics of electricity service is that the customer has no way of telling how the kilowatt hours he or she is consuming were produced. From the customer's perspective, a nuclear kilowatt hour is indistinguishable from a solar or a coal kilowatt hour. To misquote a familiar observation made many years ago, nuclear power is just another way to generate electricity.[1] This means that nuclear technology cannot stand out from the other ways to generate electricity. It must be competitive economically, or else customers won't be interested. In other words, the discipline of the marketplace imposes on nuclear energy a requirement to conform.

[1] The actual quote: nuclear power is 'just another way to boil water'.

But in other respects, of course, nuclear energy is exceptional. Because of the circumstances of its birth, and because of its special characteristics, nuclear technology and materials have always required special treatment. And separate institutions and laws have been created to manage and regulate it, with government generally playing a more prominent role than in other domains of energy technology.

The degree of separation of the nuclear energy enterprise from the rest of the electric power industry varies from one country to another. For example, in countries where the entire electricity sector has been state- owned and operated, the separation has often been less pronounced. There are also differences among countries in the degree of public management of nuclear generation and fuel cycle activities. But some measure of separation exists everywhere. As an industrial enterprise, nuclear is unlike any other.

This paradoxical linking together of the exceptional and the mundane, and the tensions inherent within it, have been present throughout the first fifty years of the nuclear industry. And they have been exploited by both nuclear opponents and advocates. Opponents have criticized the nuclear enterprise for, in effect, not being special enough. They have accused the nuclear industry of being insufficiently careful in its stewardship of the technology. They have pushed for more stringent oversight of nuclear operating organizations and nuclear technology, and they have sought to prevent the development of the industry along certain trajectories. Many of these interventions have no doubt been well-intentioned. But some activists have been motivated by the recognition that in the final analysis nuclear must be competitive, and that by forcing cost increases, regardless of whether they are justified, they can achieve their ultimate goal of shutting down the industry.

Supporters of nuclear power have also found opportunities in the paradox. They have sometimes used the special character of nuclear to argue that, in effect, it shouldn't have to compete with other sources of energy. And, perhaps because of the long years spent behind the protective cloak of government, a curious disconnection from the real world has sometimes been evident; nuclear people have been known to forget that nuclear technology is producing a fungible commodity, for which the key criterion in the marketplace is price.

For the most part, these tensions have been managed reasonably well. During the next 50 years, however, the inherent contradictions between nuclear exceptionalism and the generic nature of the nuclear product will almost certainly become more acute, because of two major developments: (1) the worldwide trend towards the introduction of competitive markets for wholesale electricity generation; and (2) the transformed international security environment. As a result of these two factors, the civilian nuclear enterprise will increasingly be subject to the forces of market competition, while simultaneously requiring even more meticulous stewardship and vigilant protection against those of malevolent intent.

Squaring this circle will require leadership and statesmanship on the part of the nuclear community and, it should also be said, a willingness to reconsider previously strongly held positions.

The third major factor that will affect the environment for nuclear power over the next half-century is the prospect of global climate change, induced by greenhouse gas emissions. And it is here that I turn to my main topic, since this prospect was the starting point of the MIT Study on the Future of Nuclear Power.[2]

The members of our interdisciplinary study group at MIT, which began its work in late 2001 and completed it this past summer, note the increasingly broad scientific consensus that greenhouse gas emissions must be reduced if the world is to avoid serious ecological and economic harm. We further expect that the U.S. will eventually join with other nations in the effort to do this.

When it comes to electricity generation, for at least the next several decades there are only a few realistic options for reducing CO2 emissions:

(1) increased efficiency of electricity generation and use
(2) expanded use of renewables
(3) continued use of fossil fuels, coupled with carbon capture and sequestration
(4) increased use of nuclear power

[2] Report of the Nuclear Power Study Group, *The Future of Nuclear Power,* Massachusetts Institute of Technology, 2003.

The purpose of our study was not to predict which of these options will ultimately prevail. Nor was it to argue the case for one or more of them relative to the others. In fact, we take the view that all of these options will almost certainly be required if the threat of global climate change is to be dealt with, and that it would therefore be a serious mistake to eliminate any of them from an overall carbon emissions strategy.

The question we set ourselves was narrower: What actions must be taken to make nuclear power a significant option for meeting increased global electricity demand while reducing greenhouse gas (GHG) emissions?

At present the prospects for nuclear to play such a role are not promising. Official forecasts call for a rapid increase in world electricity use in the coming decades – perhaps by as much as 75% by the year 2020. But those same official forecasts call for a mere 5% increase in nuclear generating capacity over that same period. Unless major additional investments in new nuclear construction are made in the relatively near future, the supply of nuclear electricity will begin to decline after that point as existing reactors are retired. While some countries, such as South Korea, Finland, India, and China, are on a path to construct new reactors, other important nuclear countries are either committed to or resigned to phasing out nuclear power gradually.

If the current situation is to be reversed, four major challenges will have to be overcome:

- the problem of economic competitiveness
- concerns over nuclear safety
- the problem of nuclear waste disposal
- and concerns over proliferation risks

The main focus of the MIT study was to examine these issues and to identify what would be needed to overcome them.

To make things more concrete, we postulated a global growth scenario that by the year 2050 would have about 1000 GWe of nuclear capacity deployed worldwide (this is a little less than 3 times the current installed base). There is nothing magic about this number. And it is not intended to be a prediction. But if nuclear plants were deployed on this scale, they would make a significant contribution to GHG reduction. For example, if the nuclear plants were displacing an equivalent quantity of coal-fired generation, about 1.8 GT of carbon emissions would be avoided per year, or roughly 25% of the expected increase in anthropogenic carbon emissions in a 'business as usual" scenario, assuming no capture and sequestration of carbon dioxide combustion products. (For comparison, global emissions of GHG today are about 6 GT of carbon equivalent.)

Another way to think about the 1000 GWe figure is that it would mean that nuclear would roughly maintain its current share of the world electricity market in the mid-century time frame (actually it would increase slightly, from 17% to 19%).

An illustrative deployment of the 1000 GWe of nuclear capacity is shown in Table 1. The precise numbers are less important than the general picture, which broadly speaking is that when trends in population and economic growth are taken into account, it is effectively impossible to achieve an overall level of nuclear deployment large enough to make a significant contribution to reducing GHG emissions unless all four of the following developments take place: (1) a continued commitment to nuclear power growth in Japan and the other advanced economies in East Asia, (2) a renewal of nuclear investment in Europe; (3) a large deployment in the most populous emerging economies (e.g., China, Indonesia, India, Brazil); and (4) a revival and major expansion of nuclear power in the U.S.

The MIT report does not say that these developments should happen, nor that they will happen. But it does indicate what would have to happen if nuclear is to have a significant impact on global warming.

We can say the same thing in a different way: to have a meaningful nuclear option (meaningful, that is, in terms of its ability to contribute significantly to reducing greenhouse gas emissions) it is necessary to plan for growth. And what the global growth scenario enables us to do is to analyze the major challenges scaled to the level at which nuclear actually would make a meaningful contribution to solving the problem of global warming.

In the time remaining I will briefly and selectively sketch some of the key findings and recommendations of the MIT study.

## Economic Competitiveness

In the crucial area of economic competitiveness, the study finds that:

- nuclear power is not now cost competitive with either coal or natural gas in deregulated markets;
- plausible but so far unproven reductions in capital cost, O&M costs, and construction lead times could significantly reduce that gap, though not eliminate it;
- such improvements, if combined with policies that internalized the social cost of carbon emissions, for example through a carbon tax or an equivalent 'cap and trade' system, could make nuclear power cost competitive.

To reach these conclusions, we built an economic model to evaluate the real levelized cost of electricity from alternative sources. The model simulates the economic conditions that investors committing funds to merchant plants in competitive markets in the United States would realistically face today. The model assumes that construction and operating cost and performance risk will be held by private investors, which implies a higher cost of capital than would generally be incurred either by government-owned utilities or by investor-owned utilities subject to cost-of-service regulation.

Under economic conditions typical of the U.S., and using parameters based on the most recent actual nuclear construction experience, rather than on engineering estimates of what might be achieved in the future under ideal conditions, we estimate that nuclear is as much as 50% more expensive than conventional pulverized coal or natural gas. This assumes a lifetime average capacity factor of 85% and a 40-year operating lifetime.

The cost improvements noted in the slide would bring the cost down very significantly. We regard these improvements as plausible, although they are not proven and in light of past experience one has to be an optimist to believe them. But there is nothing wrong with optimism. The table also shows the impact on nuclear competitiveness of taxing emissions. Taxes (or carbon sequestration costs) of $50 per ton of C or more would clearly significantly affect the relative competitiveness of nuclear.

## Safety

On the issue of safety, the report has somewhat less to say. We think that the expected number of accidents involving a serious release of radioactivity from all fuel cycle activity would have to remain at one or less over the next 50 years if the global growth scenario is to be viable. Given the magnitude of the deployment, this in turn implies the need for a ten-fold reduction in the expected frequency of serious reactor core accidents. We judge that this is achievable with advanced light water reactor plants, and that other designs such as the modular HTGR offer the prospect of even better safety performance.

But achieving this safety standard will also require development of the necessary workforce, highly competent managers, and effective management processes. This has been an area of vulnerability even in advanced economies, and it is likely also to be a major challenge in the developing economies that will need to participate in the nuclear growth scenario.

It will also require more attention to the safety of fuel cycle facilities, especially reprocessing plants.

## Nuclear Waste Management

Slow progress on waste disposal is clearly one of the main obstacles to the nuclear growth scenario. In our own opinion survey (about which I will have more to say later), almost two thirds of the respondents said they didn't think that nuclear waste could be stored safely for the long periods required.

Our report concurs with the many independent expert assessments which have concluded that mined geologic repositories will in fact be capable of safely isolating waste.

We analyzed both the once through and closed fuel cycles from a waste management point of view, and concluded that a convincing case has not been made, on the basis of waste management considerations alone, that the benefits of advanced fuel cycles featuring partitioning and transmutation would outweigh the associated safety, environmental, and security risks and the increased economic costs.

It is possible that future technological advances would change this assessment. And we can expect that the trade-offs involved will be evaluated differently in different societies, which may have different preferences and which certainly confront different constraints – whether geological, demographic, political, or economic.

But for our fundamental conclusion to change, not only would the long-term risks from geologic repositories have to be considerably higher than the performance assessments currently indicate, but also the incremental costs and short-term safety and environmental risks associated with partitioning and transmutation would have to be much lower than current analyses suggest.

There is also another conclusion: waste management strategies are potentially available in the once through cycle that could offer benefits at least as great as those claimed for advanced versions of the closed fuel cycle, with fewer short term risks and lower costs besides. A promising example of the possibilities here is the deep borehole variant of the geologic disposal approach.

## Nuclear Weapons Proliferation

Three proliferation-related issues are of particular concern in the global growth scenario:

- stocks of separated plutonium that are directly usable for weapons;
- nuclear facilities with inadequate controls;
- the transfer of technology, especially enrichment and reprocessing technology, that brings nations closer to a nuclear weapons capability.

The risks in the global growth scenario are underlined by the fact that in this scenario nuclear power would have to be introduced and developed in many countries with a broad range of security circumstances.

Our principal finding is that nuclear power can expand as envisioned in a global growth scenario with acceptable incremental proliferation risk, if built primarily on the once-through thermal reactor fuel cycle and if combined with strong safeguards and security measures.

At the present time, however, we judge that the international safeguards and nonproliferation regime is not adequate to meet the security challenges posed by the global growth scenario. Among the features of this regime that are in need of serious reconsideration is the historical presumption that everything which is not explicitly prohibited is permitted. The viability of the global growth scenario will depend in part on a re-evaluation of this fundamental point, especially as it relates to the spread of enrichment and PUREX/MOX fuel cycle technologies.

## Fuel Cycle Conclusion

These findings in the areas of economic competitiveness, waste, safety, and proliferation lead to the important general conclusion:

*Over at least the next 50 years, the best choice to meet these challenges [economic, safety, waste, proliferation] is the open, once-through fuel cycle.*

We recommend that priority be given to the open fuel cycle architecture at least until mid-century or so, with the advanced closed fuel cycles possibly deployed later, but only if significant improvements are realized through research. We judge that there are adequate uranium resources available at reasonable cost to support this choice under a global growth scenario.

## Public Opinion

On the question of public attitudes, it is abundantly clear that the viability of the global growth scenario will depend on whether the general public has adequate confidence in the safety of nuclear technology.

In the United States, independent opinion surveys show a mixed view of nuclear power. A majority of Americans simultaneously approve the use of nuclear power but oppose building more plants. This is clearly a significant obstacle to nuclear expansion and will need to change. As part of the MIT study, we conducted our own survey of 1350 American adults. We found the same level of skepticism that other surveys have found. The respondents on average preferred that nuclear power use be reduced somewhat, although it should be added that they also had the same view of coal and oil. They were neutral on natural gas, and strongly supported the growth of renewables.

We then asked a series of questions designed to reveal what these attitudes depend on. The most interesting finding was a negative one. The public's view about global warming does not predict attitudes towards nuclear power. If you divide the public into two groups, those who are concerned about global warming and those who aren't, there is no significant difference in the degree of support for nuclear power. In other words, the carbon-free character of nuclear power – the major motivation for our study – does not appear to motivate the U.S. public to favor expansion of the nuclear option.

## Recommendations

Now to our recommendations:

On the issue of economic competitiveness, our main recommendation is that the U.S. government should provide a modest financial incentive to first movers to demonstrate the cost and regulatory feasibility of new nuclear plants. We propose a production tax credit of up to $200 per kwe for up to 10 first mover plants. This benefit could be paid out at about 1.7 cents per kilowatt hour for the first year and a half of full power plant operation. We prefer the production tax credit mechanism because it offers the greatest incentive for projects to be completed – there is no subsidy if the plant is not completed and operated -- and because it can be extended to other carbon-free technologies (wind power projects actually already enjoy a 1.7 cents/kwh tax credit for the first ten years of their life.) A 1.7 cent credit is equivalent to a credit of $70 per avoided metric ton of carbon emissions, if the electricity would otherwise be generated by coal plants. (Of course, while our proposed tax credit would cease after the first year and a half of operation, the carbon emission reduction effect would continue for the rest of the life of the nuclear plant – perhaps 50 years or more – without public subsidy.) This measure will be effective in stimulating additional nuclear investment if – and only if – the industry can live up to its own expectations of being able to reduce the capital cost of new nuclear plants considerably.

On the issue of waste, we have two important recommendations. First, we call for an explicit strategy to store spent fuel for a period of several decades before further processing or disposal. Building long-term storage into the waste management system architecture by creating a network of centralized storage facilities in the U.S. and internationally will create additional flexibility and provide additional benefits besides.

Second, to prepare the way for a major expansion of nuclear power the U.S. waste management program should look beyond Yucca Mountain, where it has understandably been exclusively focused for 15 years, and should be broadened to address both incremental improvements to the current mined repository approach as well as alternatives to it. For example, we recommend an aggressive program of research on deep borehole disposal.

On the issue of proliferation, our report calls for a number of actions to strengthen the IAEA safeguards system, including adoption of the Additional Protocol, a move to a worldwide system of continuous real-time materials protection, control and accounting using surveillance and containment systems going well beyond the current system of accounting, reporting, and periodic inspections, the allocation of safeguards resources using a risk-based framework, and a refocusing of the IAEA so as to deal overwhelmingly with safety and safeguards, functions for which it is uniquely positioned by virtue of its bilateral agreements and UN affiliation. More broadly, the report calls for a reexamination of the NPT/Atoms for Peace/IAEA safeguards framework as it pertains to nuclear fuel cycle development. As Energy Secretary Abraham suggested in his speech at the UN last month:

> "We also may need to think about new approaches to the fuel cycle that strictly limit the use of enrichment and reprocessing and access to nuclear weapons technology ... while ensuring that nuclear medicine, agriculture, energy supplies, and other critical benefits can be enjoyed in all responsible nations."

Finally, with respect to research, our most important recommendation is that the U.S. government should establish a Nuclear System Modeling project to carry out the analysis, research, simulation, and collection of engineering data needed to evaluate all fuel cycles from the viewpoint of cost, safety, waste management, and proliferation resistance.

## A Final Word

These recommendations (and the others in our report) have been criticized by some for going too far, and by others for not going far enough. Many people find something to disagree with. On the other hand, the report has already begun to have an impact in some specific areas. A first mover production tax credit of 1.8 cents per kilowatt hour for new nuclear plants was incorporated into the recent Energy Bill, as was a provision for a feasibility study of deep borehole disposal. The Department of Energy appears to have abandoned its proposal that would have led to a 2000 tonne/year commercial reprocessing plant by the year 2015, and seems to be preparing to ramp up its support for fuel cycle analysis, modeling and simulation. And so on.

But our report is more than a shopping list of individual items. It is an attempt to chart out a coherent way forward for nuclear. We believe, in fact, that the development pathway we have sketched out is more likely than any other to lead to the exercise of the nuclear option on a large scale in the future. We didn't and don't expect to persuade everyone of the merits of this pathway. But if the report stimulates constructive discussion about these issues and how to move forward, we will have succeeded in our goal.