The *Nuclear*

A threefold expansion of nuclear power could contribute significantly to staving off climate change by avoiding one billion to two billion tons of carbon emissions annually

BY JOHN M. DEUTCH AND ERNEST J. MONIZ

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▶ **Governments and utilities are considering a new wave of nuclear power plant construction to help meet rising electricity demand.**

Nuclear power supplies a sixth of the world's electricity. Along with hydropower (which supplies slightly more than a sixth), it is the major source of "carbon-free" energy today. The technology suffered growing pains, seared into the public's mind by the Chernobyl and Three Mile Island accidents, but plants have demonstrated remarkable reliability and efficiency recently. The world's ample supply of uranium could fuel a much larger fleet of reactors than exists today throughout their 40- to 50-year life span.

With growing worries about global warming and the associated likelihood that greenhouse gas emissions will be regulated in some fashion, it is not surprising that governments and power providers in the U.S. and elsewhere are increasingly considering building a substantial number of additional nuclear power plants. The fossil-fuel alternatives have their drawbacks. Natural gas is attractive in a carbon-constrained world because it has lower carbon

OVERVIEW

- Global electricity consumption is projected to increase 160 percent by 2050.
- Building hundreds of nuclear power plants will help meet that need without large new emissions of carbon dioxide.
- This scenario requires economical new plants, a plan for waste storage and prevention of nuclear weapons proliferation.

Option

content relative to other fossil fuels and because advanced power plants have low capital costs. But the cost of the electricity produced is very sensitive to natural gas prices, which have become much higher and more volatile in recent years. In contrast, coal prices are relatively low and stable, but coal is the most carbon-intensive source of electricity. The capture and sequestration of carbon dioxide, which will add significantly to the cost, must be demonstrated and introduced on a large scale if coal-powered electricity is to expand significantly without emitting unacceptable quantities of carbon into the atmosphere. These concerns raise doubts about new investments in gas- or coal-powered plants.

All of which points to a possible nuclear revival. And indeed, more than 20,000 megawatts of nuclear capacity have come online globally since 2000, mostly in the Far East. Yet despite the evident interest among major nuclear operators, no firm orders have been placed in the U.S. Key impediments to new nuclear construction are high capital costs and the uncertainty surrounding nuclear waste management. In addition, global expansion of nuclear power has raised concerns that nuclear weapons ambitions in certain countries may inadvertently be advanced.

In 2003 we co-chaired a major Massachusetts Institute of Technology study, *The Future of Nuclear Power,* that analyzed what would be required to retain the nuclear option. That study described a scenario whereby worldwide nuclear power generation could triple to one million megawatts by the year 2050, saving the globe from emissions of between 0.8 billion and 1.8 billion tons of carbon a year, depending on whether gas- or coal-powered plants were displaced. At this scale, nuclear power would significantly contribute to the stabilization of greenhouse gas emissions, which requires about seven billion tons of carbon to be averted annually by 2050 [see "A Plan to Keep Carbon in Check," by Robert H. Socolow and Stephen W. Pacala, on page 50].

More than 20,000 megawatts of nuclear capacity have come online globally since 2000.

The Fuel Cycle

IF NUCLEAR POWER is to expand by such an extent, what kind of nuclear plants should be built? A chief consideration is the fuel cycle, which can be either open or closed. In an open fuel cycle, also known as a once-through cycle, the uranium is "burned" once in a reactor, and spent fuel is stored in geologic repositories. The spent fuel includes plutonium that could be chemically extracted and turned into fuel for use in another nuclear plant. Doing that results in a closed fuel cycle, which some people advocate [see "Smarter Use of Nuclear Waste," by William H. Hannum, Gerald E. Marsh and George S. Stanford; SCIENTIFIC AMERICAN, December 2005].

Some countries, most notably France, currently use a closed fuel cycle in which plutonium is separated from the spent fuel and a mixture of plutonium and uranium oxides is subsequently burned again. A longer-term option could involve recycling all the transuranics (plutonium is one example of a transuranic element), perhaps in a so-called fast reactor. In this approach, nearly all the very long lived components of the waste are eliminated, thereby transforming the nuclear waste debate. Substantial research and development is needed, however, to work through daunting technical and economic challenges to making this scheme work.

Recycling waste for reuse in a closed cycle might seem like a no-brainer: less raw material is used for the same total power output, and the problem of long-term storage of waste is alleviated because a smaller amount of radioactive material must be stored for many thousands of years. Nevertheless, we believe that an open cycle is to be preferred over the next several decades. First, the recycled fuel is more expensive than the original uranium. Second, there appears to be ample uranium at reasonable cost to sustain the tripling in global nuclear power generation that we envisage with a once-through fuel cycle for the entire lifetime of the nuclear fleet (about 40 to 50 years for each plant). Third, the environmental benefit for long-term waste storage is offset by near-term risks to the environment from the complex and highly dangerous reprocessing and fuel-fabrication operations. Finally, the reprocessing that occurs in a closed fuel cycle produces plutonium that can be diverted for use in nuclear weapons.

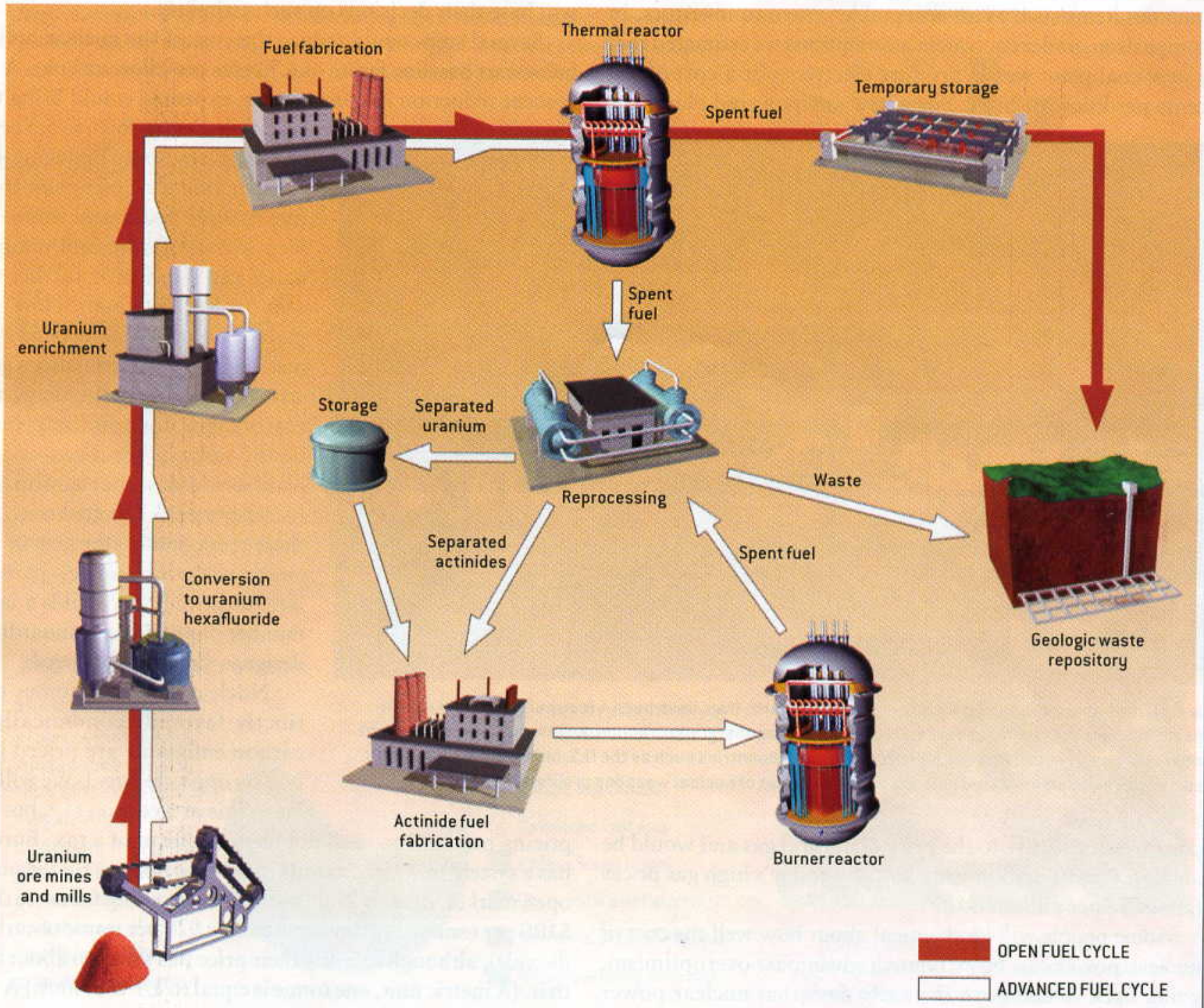
The type of reactor that will continue to dominate for at least two decades, probably longer, is the light-water reactor, which uses ordinary water (as opposed to heavy water, containing deuterium) as the coolant and moderator. The vast majority of plants in operation in the world today are of this type, making it a mature, well-understood technology.

Reactor designs are divided into generations. The earliest prototype reactors, built in the 1950s and early 1960s, were often one of a kind. Generation II reactors, in contrast, were commercial designs built in large numbers from the late 1960s to the early 1990s. Generation III reactors incorporate design improvements such as better fuel technology and passive safety, meaning that in the case of an accident the reactor shuts itself down without requiring the operators to intervene. The first generation III reactor was built in Japan in 1996. Generation IV reactors are new designs that are currently being researched, such as pebble-bed reactors and lead-cooled fast reactors [see "Next-Generation Nuclear Power," by James A.

PREFERRED FUEL CYCLES

The authors prefer an open fuel cycle for the next several decades: the uranium is burned once in a thermal reactor, and the spent fuel is stored in a waste repository [*red path*]. Some countries currently use a closed cycle in which plutonium is extracted from spent fuel and mixed with uranium for reuse in a thermal reactor [*not shown*].

An advanced closed cycle [*white path*] might become feasible and preferred in the distant future: plutonium and other elements [actinides] and perhaps the uranium in spent fuel would be reprocessed and used in special burner reactors, dramatically reducing the quantity of waste requiring long-term storage.



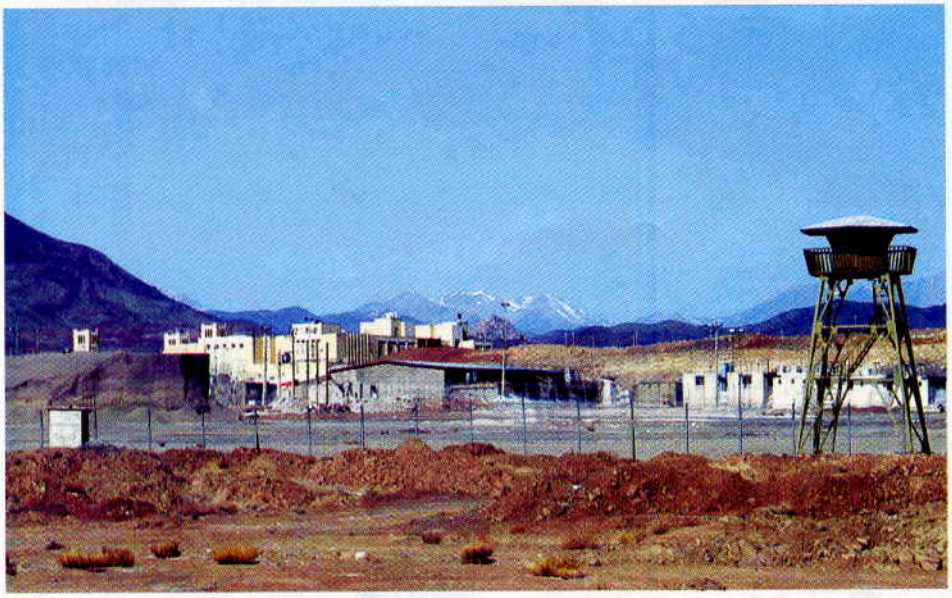
Lake, Ralph G. Bennett and John F. Kotek; SCIENTIFIC AMERICAN, January 2002]. In addition, generation III+ reactors are designs similar to generation III but with the advanced features further evolved. With the possible exception of high-temperature gas reactors (the pebble bed is one example), generation IV reactors are several decades away from being candidates for significant commercial deployment. To evaluate our scenario through to 2050, we envisaged the building of generation III+ light-water reactors.

The pebble-bed modular reactor introduces the interesting prospect of modular nuclear plants. Instead of building a massive 1,000-megawatt plant, modules each producing around 100 megawatts can be built. This approach may be particularly attractive, both in developing countries and in deregulated industrial countries, because of the much lower capital costs involved. The traditional large plants do have the advantage of economy of scale, most likely resulting in lower cost per kilowatt of capacity, but this edge could be challenged if efficient factory-style production of large numbers of modules could be implemented. South Africa is scheduled to begin construction of a 110-megawatt demonstration pebble-bed plant in 2007, to be completed by 2011, with commercial modules of about 165 megawatts planned for 2013. The hope is to sell modules internationally, in particular throughout Africa.

Reducing Costs

BASED ON PREVIOUS EXPERIENCE, electricity from new nuclear power plants is currently more expensive than that from new coal- or gas-powered plants. The 2003 M.I.T. study estimated that new light-water reactors would produce electricity at a cost of 6.7 cents per kilowatt-hour. That figure includes all the costs of a plant, spread over its life span, and includes items such as an acceptable return to investors. In comparison, under equivalent assumptions we estimated that a new coal plant would produce electricity at a cost of 4.2 cents per kilowatt-hour. For a new gas-powered plant, the cost is very sensitive to the price of natural gas and would be about 5.8 cents per kilowatt-hour for today's high gas prices (about $7 per million Btu).

Some people will be skeptical about how well the cost of nuclear power can be estimated, given past overoptimism, going back to claims in the early days that nuclear power would be "too cheap to meter." But the M.I.T. analysis is grounded in past experience and actual performance of existing plants, not in promises from the nuclear industry. Some might also question the uncertainties inherent in such cost projections. The important point is that the estimates place the three alternatives—nuclear, coal and gas—on a level playing field, and there is no reason to expect unanticipated contingencies to favor one over the other. Furthermore, when utilities are deciding what kind of power plant to build, they will base their decisions on such estimates.



▲ Activities at this uranium enrichment plant in Natanz, Iran, have been a focus of concern in recent years because the facility could be used to make weapons-grade uranium. An international agreement whereby "user" countries lease fuel from "supplier" countries such as the U.S. instead of building their own enrichment plants would help alleviate the threat of nuclear weapons proliferation.

Several steps could reduce the cost of the nuclear option below our baseline figure of 6.7 cents per kilowatt-hour. A 25 percent reduction in construction expenses would bring the cost of electricity down to 5.5 cents per kilowatt-hour. Reducing the construction time of a plant from five to four years and improvements in operation and maintenance can shave off a further 0.4 cent per kilowatt-hour. How any plant is financed can depend dramatically on what regulations govern the plant site. Reducing the cost of capital for a nuclear plant to be the same as for a gas or coal plant would close the gap with coal (4.2 cents per kilowatt-hour). All these reductions in the cost of nuclear power are plausible—particularly if the industry builds a large number of just a few standardized designs—but not yet proved.

Nuclear power becomes distinctly favored economically if carbon emissions are priced [*see box on opposite page*]. We will refer to this as a carbon tax, but the pricing mechanism need not be in the form of a tax. Europe has a system in which permits to emit carbon are traded on an open market. In early 2006 permits were selling for more than $100 per tonne of carbon emitted (or $27 per tonne of carbon dioxide), although recently their price has fallen to about half that. (A metric unit, one tonne is equal to 1.1 U.S. tons.) A tax of only $50 per tonne of carbon raises coal-powered electricity to 5.4 cents per kilowatt-hour. At $200 per tonne of carbon, coal reaches a whopping 9.0 cents per kilowatt-hour. Gas fares much better than coal, increasing to 7.9 cents per kilowatt-hour under a $200 tax. Fossil-fuel plants could avoid the putative carbon tax by capturing and sequestering the carbon, but the cost of doing that contributes in the same way that a tax would [see "Can We Bury Global Warming?" by Robert H. Socolow; SCIENTIFIC AMERICAN, July 2005].

Because it is many years since construction of a nuclear plant was embarked on in the U.S., the companies that build the first few new plants will face extra expenses that subsequent operators will not have to bear, along with additional risk in working through a new licensing process. To help over-

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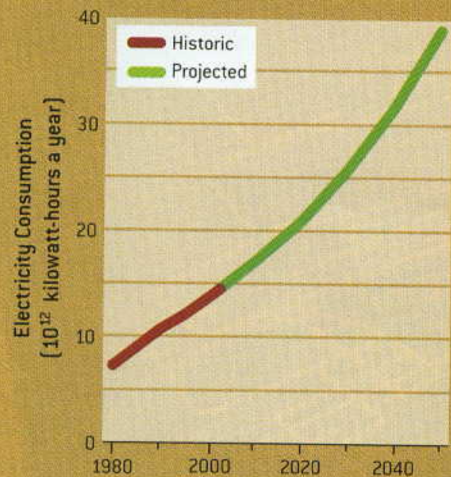
INTO THE FUTURE

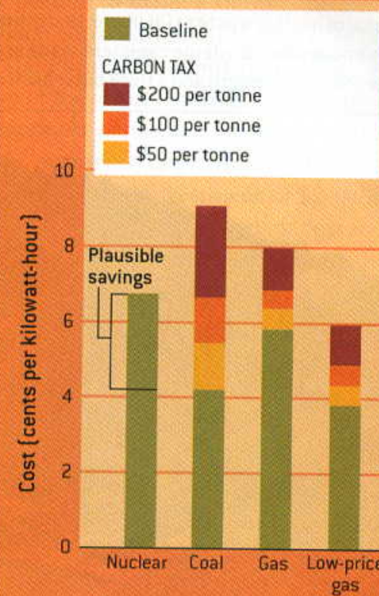
The global demand for electricity will increase substantially in the coming decades (*below*). To meet that demand, thousands of new power plants must be built. One of the most significant factors in determining what kind of facilities are built will be the estimated cost of the electricity produced (*right*). Nuclear plants will not be built in large numbers if they are not economically competitive with coal- and gas-powered plants. If nuclear plants can be made competitive, global nuclear power production might triple from 2000 to 2050, a scenario evaluated by an M.I.T. study (*bottom*).

ELECTRICITY CONSUMPTION

Global use of electricity is projected to increase 160 percent by 2050. The projection (*green*) uses United Nations population estimates and assumes that consumption per capita increases by about 1 percent annually in developed countries. Higher rates of increase are assumed for developing countries while they catch up to the developed world's usage levels.



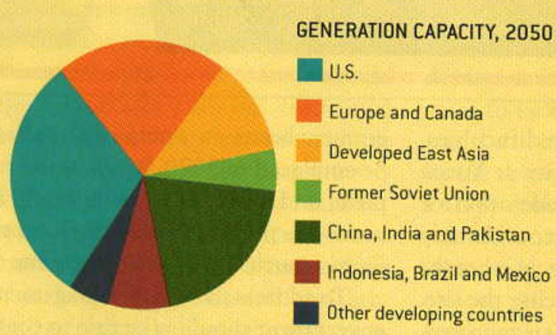
PAYING THE PIPER



The cost of electricity projected for newly built power plants depends on many factors. Taxes on carbon emissions could raise costs for coal and gas. Nuclear may be reduced by plausible but unproved cost-cutting steps.

WHO WILL HAVE THE POWER?

The M.I.T. scenario projects that the U.S. will produce about a third of the one million megawatts of electricity that will be generated by nuclear power in 2050 and that the rest of the developed world will provide another third.



▲ Under construction: an advanced (generation III+) 1,600-megawatt nuclear power plant in Olkiluoto, Finland.

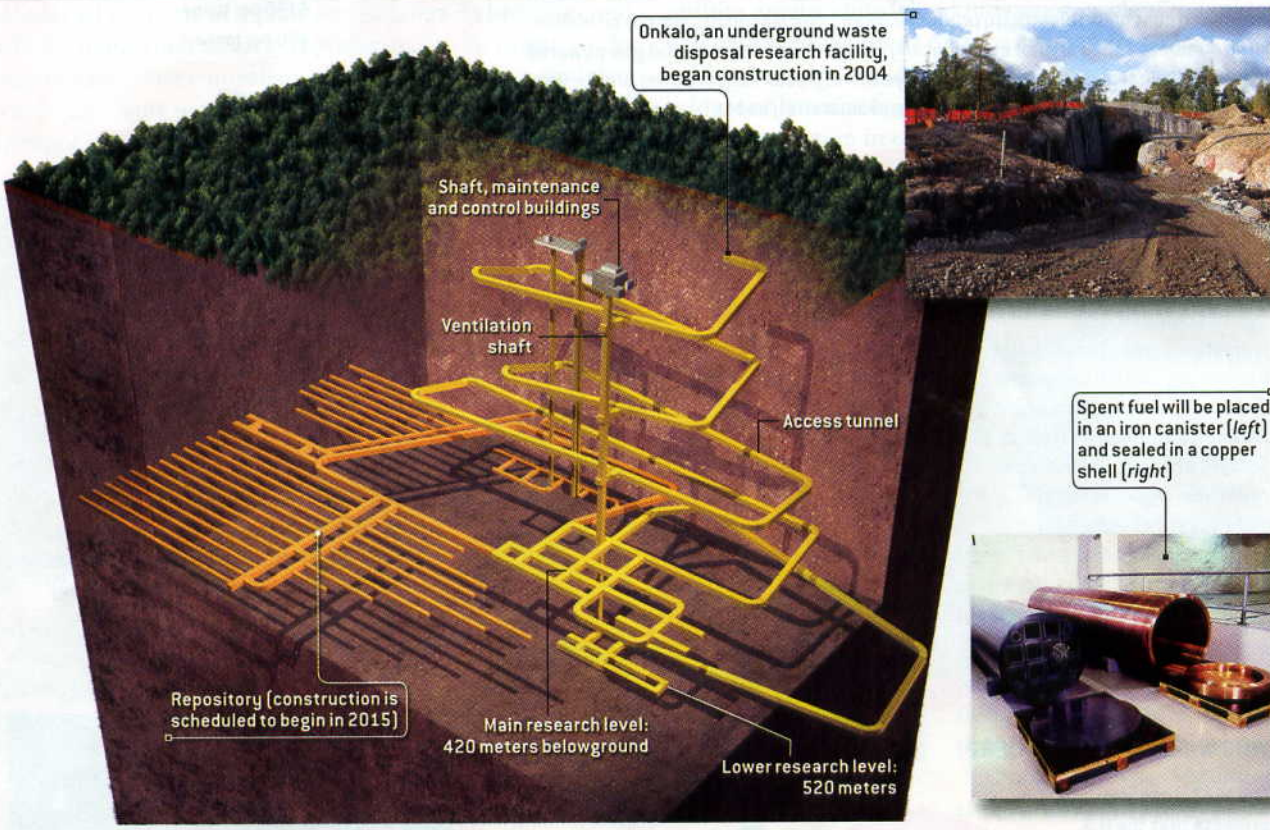
come that hurdle, the Energy Policy Act of 2005 included a number of important provisions, such as a tax credit of 1.8 cents per kilowatt-hour to new nuclear plants for their first eight years of operation. The credit, sometimes called a first-mover incentive, applies to the first 6,000 megawatts of new plants to come online. Several consortiums have formed to take advantage of the new incentives.

Waste Management

THE SECOND BIG OBSTACLE that a nuclear renaissance faces is the problem of waste management. No country in the world has yet implemented a system for permanently disposing of the spent fuel and other radioactive waste produced by nuclear power plants. The most widely favored approach is geologic disposal, in which waste is stored in chambers hundreds of meters underground. The goal is to prevent leakage of the waste for many millennia through a combination of engineered barriers (for example, the waste containers) and geologic ones (the natural rock structure where the chamber has been excavated and the favorable characteristics of the hydrogeologic basin). Decades of studies support the geologic disposal option. Scientists have a good understanding of the processes and events that could transport radionuclides from the repository to the biosphere. Despite this scientific confidence, the process

NUCLEAR WASTE DISPOSAL

Finland is moving ahead with a project to investigate underground disposal of nuclear waste at Olkiluoto. Under the plan, spent fuel rods will be encapsulated in large canisters made of an inner shell of iron for mechanical strength and a thick outer shell of copper to resist corrosion. The canisters will be placed in holes bored into the tunnel floors and surrounded by clay to prevent direct water flow to the canisters. The facility could begin accepting waste from Finland's four nuclear reactors in 2020.



of approving a geologic site remains fraught with difficulties.

A prime case in point is the proposed facility at Yucca Mountain in Nevada, which has been under consideration for two decades. Recently the site was found to have considerably more water than anticipated. It remains uncertain whether the Nuclear Regulatory Commission (NRC) will license the site.

Delays in resolving waste management (even if it is approved, it is unlikely that Yucca Mountain will be accepting waste before 2015) may complicate efforts to construct new power plants. By law, the government was to begin moving spent fuel from reactor sites to a repository by 1998. Failure to do so has led to a need for increased local storage at many sites and associated unhappiness among neighbors, towns and states.

Perhaps the first country to build a permanent storage site for its high-level nuclear waste will be Finland. At Olkiluoto, the location of two nuclear reactors, excavation has begun on an underground research facility called Onkalo. Extending about half a kilometer underground, the Onkalo project will involve study of the rock structure and groundwater flows and will test the disposal technology in actual deep underground conditions. If all goes according to plan and the necessary government licenses are obtained, the first canisters of waste could be emplaced in 2020. By 2130 the repository would be complete, and the access routes would be filled and sealed. The money to pay for the facility has been levied on the price of Finnish nuclear power since the late 1970s.

To address the waste management problem in the U.S., the government should take title to the spent fuel stored at commercial reactor sites across the country and consolidate it at one or more federal interim storage sites until a permanent disposal facility is built. The waste can be temporarily stored safely and securely for an extended period. Such extended temporary storage, perhaps even for as long as 100 years, should be an integral part of the disposal strategy. Among other benefits, it would take the pressure off government and industry to come up with a hasty disposal solution.

Meanwhile the Department of Energy should not abandon Yucca Mountain. Instead it should reassess the suitability of the site under various conditions and modify the project's schedule as needed. If nuclear power expanded globally to one million megawatts, enough high-level waste and spent fuel would be generated in the open fuel cycle to fill a Yucca Mountain–size facility every three and a half years. In the court of public opinion, that fact is a significant disincentive to the expansion of nuclear power, yet it is a problem that can and must be solved.

The Threat of Proliferation

IN CONJUNCTION WITH the domestic program of waste management just outlined, the president should continue the diplomatic effort to create an international system of fuel supplier countries and user countries. Supplier countries such as the U.S., Russia, France and the U.K. would sell fresh fuel to user countries with smaller nuclear programs and commit to removing the spent fuel from them. In return, the user countries would forgo the construction of fuel-producing facilities. This arrangement would greatly alleviate the danger of nuclear weapons proliferation because the chief risks for proliferation involve not the nuclear power plants themselves but the fuel enrichment and reprocessing plants. The current situation with Iran's uranium enrichment program is a prime example. A scheme in which fuel is leased to users is a necessity in a world where nuclear power is to expand threefold, because such an expansion will inevitably involve the spread of nuclear power plants to some countries of proliferation concern.

A key to making the approach work is that producing fuel does not make economic sense for small nuclear power programs. This fact underlies the marketplace reality that the world is already divided into supplier and user countries. Instituting the supplier/user model is largely a matter, albeit not a simple one, of formalizing the current situation more permanently through new agreements that reinforce commercial realities.

Although the proposed regime is inherently attractive to user nations—they get an assured supply of cheap fuel and are relieved of the problem of dealing with waste materials—other incentives should also be put in place because the user states would be agreeing to go beyond the requirements of the treaty on the nonproliferation of nuclear weapons. For example, if a global system of tradable carbon credits were instituted, user nations adhering to the fuel-leasing rules could be granted credits for their new nuclear power plants.

Iran is the most obvious example today of a nation that the global community would rather see as a "user state" than as a producer of enriched uranium. But it is not the only difficult case. Another nation whose program must be addressed promptly is Brazil, where an enrichment facility is under construction supposedly to provide fuel for the country's two nuclear reactors. A consistent approach to countries such as Iran and Brazil will be needed if nuclear power is to be expanded globally without exacerbating proliferation concerns.

The Terawatt Future

A TERAWATT—one million megawatts—of "carbon-free" power is the scale needed to make a significant dent in projected carbon dioxide emissions at midcentury. In the terms used by Socolow and Pacala, that contribution would correspond to one to two of the seven required "stabilization wedges." Reaching a terawatt of nuclear power by 2050 is certainly challenging, requiring deployment of about 2,000 megawatts a month. A capital investment of $2 trillion over several decades is called for, and power plant cost reduction, nuclear waste management and a proliferation-resistant international fuel cycle regime must all be addressed aggressively over the next decade or so. A critical determinant will be the degree to which carbon dioxide emissions from fossil-fuel use are priced, both in the industrial world and in the large emerging economies such as China, India and Brazil.

The economics of nuclear power are not the only factor governing its future use. Public acceptance also turns on issues of safety and nuclear waste, and the future of nuclear power in the U.S. and much of Europe remains in question. Regarding safety, it is essential that NRC regulations are enforced diligently, which has not always been the case.

In the scenario developed as part of the M.I.T. study, it emerged that the U.S. would approximately triple its nuclear deployment—to about 300,000 megawatts—if a terawatt were to be realized globally. The credibility of such a scenario will be largely determined in the forthcoming decade by the degree to which the first-mover incentives in the 2005 Energy Policy Act are exercised, by the capability of the government to start moving spent fuel from reactor sites and by whether the American political process results in a climate change policy that will significantly limit carbon dioxide emissions. SA

> Extended temporary storage of waste should be an integral part of the disposal strategy.

MORE TO EXPLORE

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Generation IV Nuclear Energy Systems: **http://gen-iv.ne.doe.gov/**

Pebble Bed Modular Reactor: **www.pbmr.co.za**

Posiva home page (Onkalo waste management project): **www.posiva.fi/englanti/**

U.S. Nuclear Regulatory Commission: **www.nrc.gov**