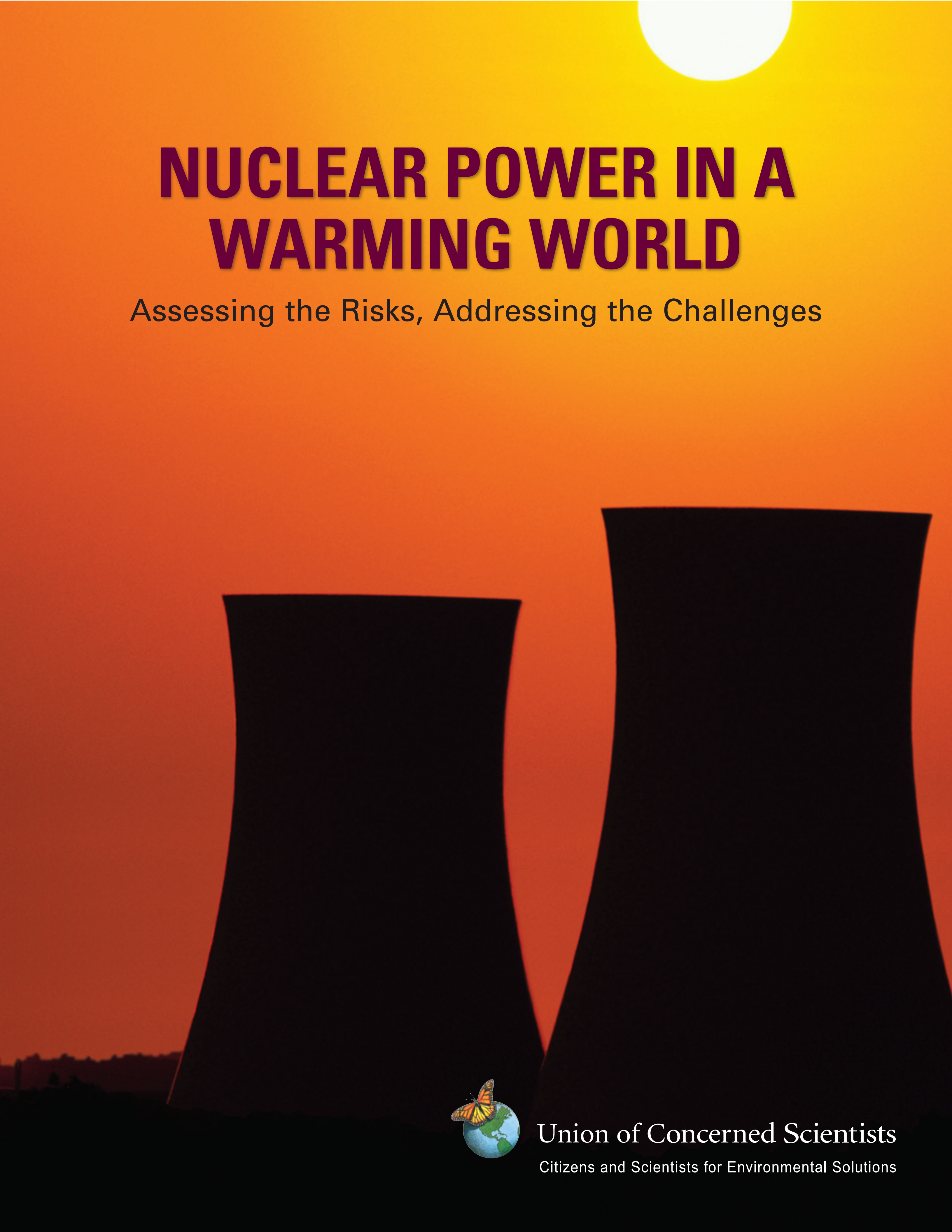

NUCLEAR POWER IN A WARMING WORLD

Assessing the Risks, Addressing the Challenges

Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

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December 2007

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The Union of Concerned Scientists is the leading science-based nonprofit working for a healthy environment and a safer world.

The UCS Global Security Program seeks to bring about a safer world by eliminating the risks posed by nuclear arsenals and nuclear terrorism, improving nuclear power plant safety, preventing the development of anti-satellite and space-based weapons, and enhancing international dialogue on security issues.

More information about the Union of Concerned Scientists and the Global Security Program is available on the UCS website at *www.ucsusa.org*. The full text of this report is available on the UCS website (in PDF format) or may be obtained from:

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Executive Summary

Findings and Recommendations in Brief

Global warming demands a profound transformation in the ways we generate and consume energy. Because nuclear power results in few global warming emissions, an increase in nuclear power could help reduce global warming—but it could also increase the threats to human safety and security. The risks include a massive release of radiation due to a power plant meltdown or terrorist attack, and the death of hundreds of thousands due to the detonation of a nuclear weapon made with materials obtained from a civilian nuclear power system. Minimizing these risks is simply pragmatic: nothing will affect the public acceptability of nuclear power as much as a serious nuclear accident, a terrorist strike on a reactor or spent fuel pool, or the terrorist detonation of a nuclear weapon made from stolen nuclear reactor materials.

The report finds that:

1. The United States has strong nuclear power safety standards, but serious safety problems continue to arise at U.S. nuclear power plants because the Nuclear Regulatory Commission (NRC) is not adequately enforcing the existing standards. The NRC's poor safety culture is the biggest barrier to consistently effective oversight, and Congress should require the NRC to bring in managers from outside the agency to rectify this problem.
2. While the United States has one of the world's most well-developed regulatory systems for protection of nuclear facilities against sabotage and attack, current security standards are inadequate to defend against credible threats. Congress should give the responsibility for identifying credible threats and ensuring that security is adequate to the Department of Homeland Security rather than the NRC.
3. The extent to which an expansion of nuclear power increases the risk that more nations or terrorists will acquire nuclear weapons depends largely on whether reprocessing is included in the fuel cycle, and whether uranium enrichment comes under effective international control. A global prohibition on reprocessing, and international ownership of all enrichment facilities, would greatly reduce these risks. The United States should reinstate a ban on reprocessing U.S. spent fuel and take the lead in forging an indefinite global moratorium on reprocessing. The administration should also pursue a regime to place all uranium enrichment facilities under international control.
4. Over the next 50 years, interim storage of spent fuel in dry casks is economically viable and secure, if hardened against attack. In the longer term, a geologic repository would provide the stability needed to isolate the spent fuel from the environment. It is critical to identify and overcome technical and political barriers to licensing a permanent repository, and the Department of Energy should identify and begin to characterize potential sites other than Yucca Mountain.
5. Of all the new reactor designs being seriously considered for deployment in the United States, only one—the Evolutionary Power Reactor—appears to have the potential to be significantly safer and more secure than today's reactors. To eliminate any financial incentives for reactor vendors to reduce safety margins, and to make safer reactors competitive in the United States, the NRC should require new U.S. reactors to be significantly safer than current reactors.
6. The proposed Global Nuclear Energy Partnership (GNEP) plan offers no waste disposal benefits and would increase the risks of nuclear proliferation and terrorism. It should be dropped.

Since its founding in 1969, the Union of Concerned Scientists (UCS) has worked to make nuclear power safer and more secure. We have long sought to minimize the risk that nations and terrorists would acquire nuclear weapons materials from nuclear power facilities. This report shows that nuclear power continues to pose serious risks that are unique among the energy options being considered for reducing global warming emissions. The future risks of nuclear energy will depend in large part on whether governments, industry, and international bodies undertake a serious effort to address these risks—including the steps outlined here—before plunging headlong into a rapid expansion of nuclear energy worldwide. In particular, the risks will increase—perhaps substantially—if reprocessing becomes part of the fuel cycle in the United States and expands worldwide.

The risks posed by climate change may turn out to be so grave that the United States and the world cannot afford to rule out nuclear power as a major contributor to addressing global warming. However, it may also turn out that nuclear power cannot be deployed worldwide on the scale needed to make a significant dent in emissions without resulting in unacceptably high safety and security risks. Resolving these questions is beyond the scope of this report, but the information provided here will help inform a necessary discussion of the risks of various energy technologies that can address global warming.

Global warming is a profound threat to both humanity and the natural world, and one of the most serious challenges humankind has ever faced. We are obligated by our fundamental responsibility to future generations and our shared role as stewards of this planet to confront climate change in an effective and timely manner. Scientists are acutely aware that the window for reducing global warming emissions to reasonably safe levels is closing quickly. Several recent analyses have concluded that, to avoid dangerous climate change, the United States and other industrialized nations will need to reduce emissions at least 80 percent by mid-century, compared with 2000 levels—and that national and international policies must be in place within the next 5 to 10 years to achieve this ambitious outcome.

Thus a profound transformation of the ways in which we generate and consume energy must begin now, and the urgency of this situation demands that we consider all possible options for minimizing climate change. However, in examining each option we must take into account its environmental and public health impacts, its potential impact on national and international security, the time required for deployment, and the costs.

Nuclear power plants do not produce global warming emissions when they operate, and the emissions associated with the nuclear fuel cycle and plant construction are quite modest (and will fall further if industry and transportation rely less on fossil fuels). Thus an expansion of nuclear power could help curb global warming. However, such an expansion could also worsen the threats to human safety and security from radioactive releases and wider access to materials that can be used to make nuclear weapons.

This report assesses the risks posed by nuclear power and proposes ways to minimize them. In particular, it considers (1) the risk of reactor accidents and how to improve government oversight of reactor safety; (2) the threat of sabotage and terrorist attacks on reactors and associated facilities, and how to improve security; (3) the potential for expanded nuclear power facilities to allow nations and terrorist groups to acquire nuclear weapons more easily, and what the United States can do to minimize those possibilities; and (4) how best to deal with the radioactive waste from U.S. power plants. This report also examines new designs for reactors and other nuclear power facilities, and considers to what extent these plants would entail fewer risks than today's designs.

Key Findings and Recommendations

1. Ensuring the Safety of Nuclear Power

The United States has strong nuclear power safety standards, but serious safety problems continue to arise at U.S. nuclear power plants because the Nuclear Regulatory Commission (NRC) is not adequately enforcing those standards.

Findings

Safety problems remain despite a lack of serious accidents.

A serious nuclear power accident has not occurred in the United States since 1979, when the Three Mile Island reactor in Pennsylvania experienced a partial core meltdown. However, the absence of serious accidents does not necessarily indicate that safety measures and oversight are adequate. Since 1979, there have been 35 instances in which individual reactors have shut down to restore safety standards, and the owner has taken a year or more to address dozens or even hundreds of equipment impairments that had accumulated over a period of years. The most recent such shutdown occurred in 2002. These year-plus closures indicate that the NRC has been doing a poor job of regulating the safety of power reactors. An effective regulator would be neither unaware nor passively tolerant of safety problems so extensive that a year or more is needed to fix them.

The most significant barrier to consistently effective NRC oversight is a poor "safety culture" at the agency itself.

The poor safety culture at the NRC manifests itself in several ways. The agency has failed to implement its own findings on how to avoid safety problems at U.S. reactors. It has failed to enforce its own regulations, with the result that safety problems have remained unresolved for years at reactors that have continued to operate. And it has inappropriately emphasized adhering to schedules rather than ensuring safety. A significant number of NRC staff members have reported feeling unable to raise safety concerns without fear of retaliation, and a large percentage of those staff members say they have suffered harassment or intimidation.

The NRC's recent curtailment of the public's right to participate in reactor licensing proceedings shuts the door to an important means of enhancing safety.

Public input has long played an important role in the NRC's process for licensing power plants. The NRC itself has identified numerous examples where public participation has improved safety. Despite this, the NRC recently removed the public's right to discovery and cross-examination during hearings on renewals of existing power plant licenses and applications for new ones, precluding meaningful public participation.

The NRC's policy on the safety of new reactors is an obstacle to ensuring better designs.

NRC policy stipulates that advanced reactors need provide only the same level of protection against accidents as today's generation of reactors, hampering the development of safer ones.

The NRC's budget is inadequate.

Congress continues to pressure the NRC to cut its budget, so it spends fewer resources on overseeing safety. The NRC does not have enough funding to fulfill its mandate to ensure safety while also responding to applications to extend the licenses of existing reactors and license new ones.

The Price-Anderson Act lessens incentives to improve safety.

The act, just renewed for another 20 years, severely limits the liability of owners for accidents at nuclear power plants. This protection lessens the financial incentives for reactor vendors to increase safety measures, and for owners to improve operating standards.

Recommendations

- To ensure that the NRC develops a strong safety culture as soon as possible and sustains it, Congress should require the NRC to bring in managers from outside the agency to establish such a culture, and evaluate them on whether they do so.
- The NRC should fully restore the public's right to discovery and cross-examination before and during hearings on changes to existing power plant licenses and applications for new ones.
- To ensure that any new nuclear plants are significantly safer than existing ones, the NRC should require that new reactors have features designed to prevent severe accidents, and to mitigate them if they occur. These design features should reduce reliance on operator interventions in the event of an accident, which are inherently less dependable than built-in measures.
- Congress should ensure that the NRC has enough resources to provide robust oversight of nuclear reactor safety, and to meet its goals for responding to requests from reactor owners in a timely manner without compromising safety.
- Congress should eliminate Price-Anderson liability protection—or substantially raise the liability limit—for new U.S. nuclear power plants, to remove financial disincentives for reactor designers and owners to improve safety.

2. Defending against Sabotage and Terrorist Attacks

While the United States has one of the world's most well-developed regulatory systems for protecting nuclear facilities against sabotage and attack, today's security standards are inadequate to defend against credible threats.

Findings

Sabotage of a nuclear reactor could result in a large release of radiation.

If a team of well-trained terrorists forcibly entered a nuclear power plant, it could disable safety systems within a matter of minutes, and do enough damage to cause a meltdown of the core, failure of the containment structure, and a large release of radiation. Such an attack could contaminate large regions for thousands of years, producing higher cancer rates and billions of dollars in associated costs.

Spent fuel pools are highly vulnerable to terrorist attack.

Unlike reactors, the pools used to store spent fuel at reactor sites are not protected by containment buildings, and thus are attractive targets for terrorist attacks. Such attacks could lead to the release of large amounts of dangerous radioactive materials into the environment.

The NRC gives less consideration to attacks and deliberate acts of sabotage than it does to accidents.

This lack of attention is manifested in emergency plans that do not take terrorist attacks into account, the agency's refusal to consider terrorist attacks as part of the environmental assessments during licensing proceedings, and its failure to adequately address the risk of an attack on spent fuel pools at reactor sites.

NRC assumptions about potential attackers are unrealistically modest.

The NRC's Design Basis Threat (DBT) defines the size and abilities of a group that might attack a nuclear facility, and against which an owner must be able to defend. Although not publicly available, before 9/11 the DBT was widely known to consist of three attackers armed with nothing more sophisticated than handheld automatic rifles, and working with a single insider whose role was limited to providing information about the facility and its defenses. The DBT has been upgraded post-9/11, but it still does not reflect real-world threats. For example, it excludes the possibility that terrorist groups would use rocket-propelled grenades—a weapon widely used by insurgents around the world.

The DBT is unduly influenced by industry perspectives and pressure.

The NRC would ideally base the DBT solely on plausible threats to nuclear facilities. However, in practice, the agency's desire to avoid imposing high security costs on the nuclear industry also affects its security requirements.

There is no assurance that reactors can be defended against terrorist attacks.

The NRC stages mock attacks to determine if plant owners can defend their reactors against DBT-level attacks. Test results reveal poor performance, and the integrity of the tests themselves is in question. The federal government is responsible for defending against attacks more severe than the DBT, but it has no mechanism for ensuring that it can provide such protection.

Recommendations

- The NRC should treat the risks of deliberate sabotage and attacks on par with the risks of accidents, and require all environmental reviews during licensing to consider such threats. The agency should also require and test emergency plans for defending against severe acts of sabotage and terrorist attacks as well as accidents.
- The NRC should require that spent fuel at reactor sites be moved from storage pools to dry casks when it has cooled enough to do so (within six years), and that dry casks be protected by earthen or gravel ramparts to minimize their vulnerability to terrorist attack.
- The Department of Homeland Security (DHS) should set the DBT. It should assess the credible threats to nuclear facilities, determine the level of security needed to protect against those threats, and assign responsibility for countering each type of threat to either industry or the federal government. To conduct its independent assessments, the DHS would need full-time staff with the necessary expertise. It would also need to address the internal problems that have hampered its past performance. The NRC would ensure that the nuclear industry complies with DHS requirements. The DHS should ensure that the government has enough resources to fulfill its responsibilities to protect nuclear facilities against credible threats as assigned by the DHS.
- The government should evaluate its ability to protect the public from attacks above the DBT level by periodically conducting tests that simulate an actual attack. The DHS should serve as an independent evaluator of such tests, analogous to the role performed by the Federal Emergency Management Agency during biennial exercises of emergency plans for nuclear plants.
- The government should establish a federally administered program for licensing private nuclear security guards that would require them to successfully complete a federally run training course and undergo periodic recertification.

3. Preventing Nuclear Proliferation and Nuclear Terrorism

The extent to which an expansion of nuclear power would raise the risk that more nations or terrorists will acquire nuclear weapons depends largely on two factors: whether reprocessing is included in the fuel cycle, and whether uranium enrichment comes under effective international control. A global prohibition on reprocessing, and international ownership of all enrichment facilities, would greatly reduce these risks.

Findings

An expansion of nuclear power could—but need not—make it more likely that more nations will acquire nuclear weapons. In any event, it is only one factor of many that will affect this outcome.

Many states that do not now have nuclear weapons already have the technical ability to produce them, should they decide to do so. In other countries without such a capability, nuclear power facilities could aid a nuclear weapons program—in some cases significantly. However, the political incentives for a nation to acquire nuclear weapons are the most significant factor, and there is little the United States or international community can do to prevent a determined nation from eventually acquiring such weapons.

The nuclear facilities that present the greatest proliferation risk are those that can be used to produce the materials needed to make nuclear weapons—plutonium and highly enriched uranium (HEU).

Reprocessing plants extract plutonium from used reactor fuel, while uranium enrichment facilities that make low-enriched uranium for reactor fuel can be used to make HEU.

An expansion of nuclear power could—but need not—make it more likely that terrorists will acquire nuclear weapons.

In any event, other sources of nuclear weapons and weapons materials exist. Because it is difficult and expensive to produce the fissile materials needed for nuclear weapons, terrorists are almost certainly unable to do so themselves. However, several countries have large military stockpiles of plutonium and HEU, or civil stockpiles of plutonium, which terrorists could steal and use to produce nuclear weapons. Terrorists could also steal a nuclear weapon, or purchase one that has been stolen.

The degree to which an expansion of nuclear power would increase the risk of nuclear terrorism depends largely on whether reprocessing is part of the fuel cycle—internationally or in the United States.

Reprocessing changes plutonium from a form in which it is highly radioactive and nearly impossible to steal to one in which it is not radioactive and could be stolen surreptitiously by an insider or taken by force during routine transportation. Building more facilities for reprocessing spent fuel and making plutonium-based reactor fuel would provide terrorists with more potential sources of plutonium, and perhaps with greater ease of access. U.S. nuclear power does not now pose a risk that terrorists will acquire material for nuclear weapons. However, the U.S. reprocessing program now being pursued by the administration would change that.

None of the proposed new reprocessing technologies would provide meaningful protection against nuclear terrorism or proliferation.

No reprocessing technology can be made as secure as directly disposing of used nuclear fuel.

Strict international controls on uranium enrichment facilities will be needed to minimize the proliferation risks associated with expanded nuclear power.

Such controls should not discriminate between nations that have nuclear weapons and those that do not.

Recommendations

- The United States should reinstate a ban on reprocessing U.S. spent fuel, and actively discourage other nations from pursuing reprocessing. The security risks associated with current and near-term reprocessing technologies are too great.
- The United States should take the lead in forging an indefinite global moratorium on operating existing reprocessing plants and building or starting up new ones. Reprocessing is not necessary for any current nuclear energy program, and the security risks associated with running reprocessing plants and stockpiling plutonium are unacceptable in today's threat environment, and are likely to remain so for the foreseeable future. A U.S. moratorium will facilitate a global moratorium.
- The administration should pursue a regime—overseen by the International Atomic Energy Agency—to internationalize all uranium enrichment facilities and to safeguard such facilities. To make such a regime attractive to nations without those facilities, it would need to be non-discriminatory, and thus cover all existing enrichment plants.

- The administration should work to complete a comprehensive Fissile Material Cutoff Treaty that prohibits the production of plutonium for any purpose—military or civil—and that institutionalizes and verifies the reprocessing moratorium.

4. Ensuring the Safe Disposal of Nuclear Waste

Over the next 50 years, interim storage of spent fuel in dry casks is economically viable and secure. However, identifying and overcoming the technical and political barriers to licensing a permanent U.S. geologic repository for nuclear waste is critical.

Findings

A permanent geologic repository is the preferred method for disposal of nuclear waste.

An underground geologic repository—if properly sited and constructed—can adequately protect the public and environment from radioactive waste for tens of thousands of years. However, a repository location must be chosen based on a high degree of scientific and technical consensus. Such a consensus does not now exist on the proposed Yucca Mountain facility in Nevada.

Reprocessing offers no advantages for nuclear waste disposal.

Reprocessing spent fuel to extract plutonium and uranium would not allow a geologic repository to accommodate more nuclear waste, as the repository would also have to accept high-level waste from reprocessing. Reprocessing would also increase the amount of material needing disposal in other engineered waste facilities.

There is no immediate need to begin operating a permanent repository.

Interim storage of spent fuel in dry casks at reactor sites hardened against attack is an economically viable and secure option for at least 50 years. However, such dry casks are not adequately protected today, and should be strengthened against attack, such as by surrounding them with an earthen berm.

Recommendations

- The United States should drop its plans to begin a reprocessing program.
- The federal government should take possession of spent fuel at reactor sites and upgrade the security of onsite storage facilities.
- Because licensing a permanent repository may take a decade or more, especially if Yucca Mountain is found unsuitable, the Department of Energy should identify and begin to characterize other potential sites.

5. Evaluating New Reactor Designs

Of all new reactor designs under consideration in the United States, at this time only one—the Evolutionary Power Reactor, which was designed to comply with more stringent European requirements—appears to have the potential to be significantly safer and more secure against attack than today's reactors. However, U.S. plant owners will have no financial incentive to build such reactors unless the NRC strengthens U.S. standards and requires that new reactors be significantly safer than today's reactors.

The administration's proposed Global Nuclear Energy Partnership (GNEP)—which would entail reprocessing U.S. spent fuel and building large numbers of new fast burner reactors to use plutonium-based fuel—offers no waste disposal benefits and would increase the risks of nuclear proliferation and terrorism.

Findings

Of all the new reactor designs, only one—the Evolutionary Power Reactor (EPR)—appears to have the potential to be significantly less vulnerable to severe accidents than today's reactors.

The Pebble Bed Modular Reactor has several attractive safety features, but outstanding safety issues must be resolved to determine whether it is likely to be safer than existing reactors. Other designs either offer no potential for significant safety improvements, or are too early in the design phase to allow informed judgment.

Of all the new reactor designs, only one—the EPR—appears to have the potential to be significantly less vulnerable to attack than today's reactors.

However, this may only remain the case if the NRC requires that new reactors be able to withstand the impact of a commercial aircraft, thus ensuring that U.S. EPRs will include the double containment structure that is part of EPRs built in Europe.

No technical fix—such as those incorporated in new reprocessing technologies—can remove the proliferation risks associated with nuclear fuel cycles that include reprocessing and the use of plutonium-based fuel.

Once separated from highly radioactive fission products, the plutonium is vulnerable to theft or diversion. New reprocessing technologies under consideration will leave the plutonium in a mixture with other elements, but these are not radioactive enough to provide theft resistance, and a nation seeking nuclear weapons could readily separate the plutonium from these elements by chemical means.

The proposed GNEP system of fast burner reactors will not result in more efficient use of waste repositories.

While the proposed GNEP system could, in principle, significantly reduce the amount of heat-producing actinides that would need disposal in a geologic repository, thus allowing it to accept more waste, this potential cannot be realized in practice. As the National Academy of Sciences and the U.S. Department of Energy have found, reducing the actinides by a meaningful amount would require operating a large system of nuclear facilities over a period of centuries, and cost hundreds of billions of dollars more than disposing of spent fuel directly.

Recommendations

- The NRC should require that new reactor designs be safer than existing reactors. Otherwise, designs with greater safety margins will lose out in the marketplace to designs that cut costs by reducing safety.
- Forthcoming NRC regulations that will require owners to integrate security measures into reactor designs if they are "practicable" should specify that the NRC—not reactor owners—will determine which measures meet that criterion.
- The NRC should require that new reactors be able to withstand the impact of a commercial aircraft.
- The United States should reinstate a ban on reprocessing U.S. spent fuel, and actively discourage other nations from pursuing reprocessing.
- The United States should eliminate its programs to develop and deploy fast reactors.

Chapter 1

Nuclear Power Today and Tomorrow

Global warming poses a profound threat to humanity and the natural world, and is one of the most serious challenges humankind has ever faced. We are obligated by our fundamental responsibility to future generations and our shared role as stewards of this planet to confront climate change in an effective and timely manner.

The atmospheric concentration of carbon dioxide—the heat-trapping gas primarily responsible for global warming—has reached levels the planet has not experienced for hundreds of thousands of years, and as a result the global mean temperature has risen steadily for more than a century. The National Academies of Science in the United States, the Intergovernmental Panel on Climate Change, and scientific academies in 10 other nations have all stated that human activity, especially the burning of fossil fuels, is a major driver of this warming trend.

Recent studies have concluded that avoiding dangerous climate change will require the United States and other industrialized countries to reduce their global warming emissions *at least* 80 percent below 2000 levels by 2050.[1] This is a demanding task: U.S. emissions are growing at an annual rate of 1 percent, putting them on track to rise to more than 50 percent above 2000 levels by 2050. The window for holding global warming emissions to reasonably safe levels is closing quickly. A profound transformation of the ways in which Americans generate and consume energy must begin now. Because nuclear power results in modest global warming emissions, one possibility is to increase the amount of U.S. electricity produced from nuclear power.

U.S. Global Warming Emissions

In 2005, energy consumption accounted for roughly 85 percent of all U.S. global warming emissions.[2] Roughly 33 percent of these emissions stemmed from the use of electricity, 28 percent from the combustion of fossil fuels for transportation, and 24 percent from fossil fuel combustion for producing steam and heat for industrial processes, and for commercial and residential heating, hot water, and cooking. Agricultural practices produced roughly 7 percent of all U.S. emissions, primarily from raising cattle (which emit methane), managing manure, and using fertilizer. The by-products of industrial processes contributed roughly 5 percent of U.S. emissions, and methane emitted from landfills some 2 percent (see Figure 1, p. 10).[3]

Roughly 86 percent of the energy Americans consumed in 2005 was generated from fossil fuels, which produce global warming emissions. Nuclear power supplied 8 percent of the total energy consumed in the United States, while hydroelectric power plants and other forms of renewable energy, including biomass, geothermal, wind, and solar, provided the remaining 6 percent (see Figure 2, p. 10).

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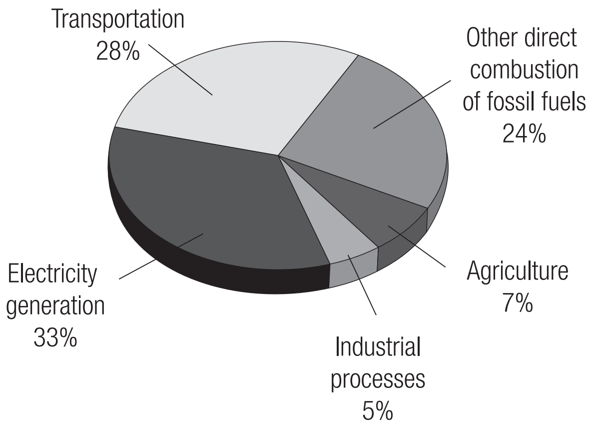
[1] Amy L. Luers, et al., *How to avoid dangerous climate change: A target for U.S. emissions reductions* (Cambridge, MA: Union of Concerned Scientists, 2007), online at *http://www.ucsusa.org/assets/documents/global_warming/emissions-target-report.pdf*.

[2] These global warming emissions include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

[3] All figures are from the executive summary of U.S. Environmental Protection Agency, “Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–2005,” EPA #430-R-07-002 (April 2007), online at *http://epa.gov/climatechange/emissions/usinventoryreport.html.*

Figure 1. U.S. Global Warming Emissions by Source, 2005



Source: U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005," EPA #430-R-07-002 (April 2007).

Improving the efficiency with which fossil fuels are converted to usable energy (supply-side efficiency), and the efficiency with which end-use applications—such as appliances, lighting, and air conditioning—consume energy (demand-side efficiency), can contribute greatly to reducing energy-related greenhouse gas emissions in the United States. However, meeting the 2050 target will require a major expansion of energy sources that either do not produce global warming gases or do so at a much-reduced level.

Nuclear Power's Share of the U.S. Energy Mix

Roughly 60 percent of the energy consumed in 2005 in the United States stemmed from the direct combustion of fossil fuels for transportation, and for industrial, commercial, and residential use. The remaining 40 percent was consumed in the form of electricity.

Of the electricity used in the United States in 2005, fossil fuels generated 70 percent, nuclear power supplied roughly 21 percent, and hydroelectric dams and other renewable energy sources provided 9 percent (see Figure 3).

The 21 percent of U.S. electricity provided by nuclear power in 2005 stemmed from the 103 reactors then operating (one more reactor began operating earlier this year) (see Figure 4). Most of these reactors have 40-year operating licenses, but several have recently received license extensions for another 20 years. Even with these extensions, the first plants will retire in 2029. Even if all 104 reactors obtain extensions, nearly all will retire by 2050.[4]

Figure 2. Total U.S. Energy Consumption by Source, 2005

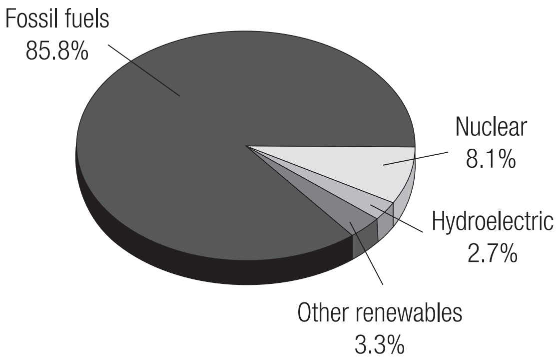
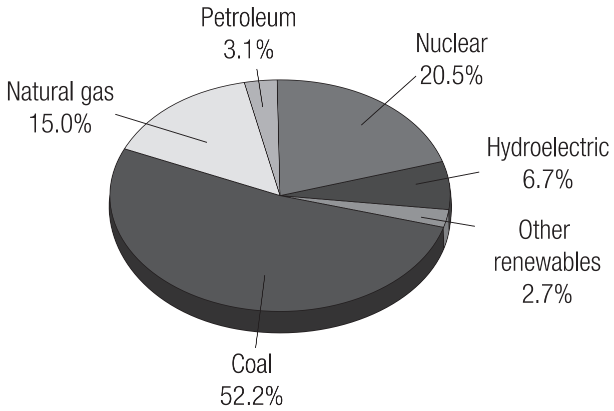


Figure 3. U.S. Electricity Consumption by Source, 2005



Source: U.S. Energy Information Administration. 2006. *Annual Energy Review 2005.*

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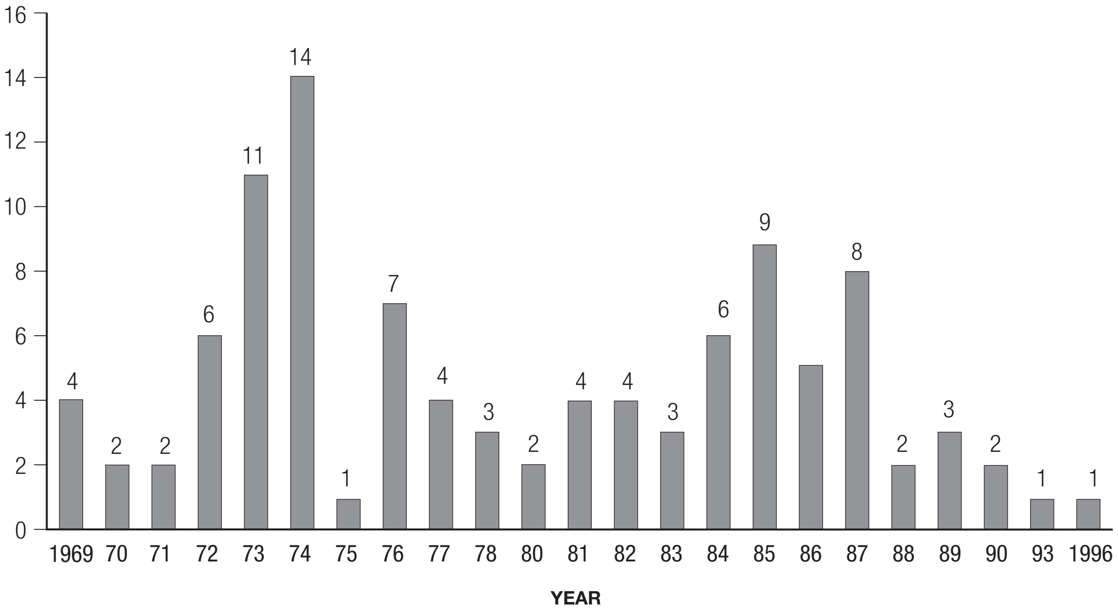
[4] Nuclear plants are unlikely to receive second license extensions, as the basic components will eventually wear out.

Figure 4. U.S. Commercial Nuclear Power Reactor Operating Licenses Issued by Year



Note: No licenses issued after 1996.

Nuclear Power and Global Warming

Nuclear power plants do not produce global warming emissions when they operate. However, producing nuclear power requires mining and processing uranium ore, enriching uranium to create reactor fuel, manufacturing and transporting fuel, and building plants—all of which consume energy. Today much of that energy is provided by fossil fuels (although that may change if the United States takes steps to address global warming).

However, the global warming emissions associated with nuclear power even now are relatively modest. Indeed, its life cycle emissions are comparable to those of wind power and hydropower. While estimates of life cycle greenhouse gas emissions vary with different assumptions and methodologies, the basic conclusions of most analyses are consistent: for each unit of electricity generated, natural gas combustion results in roughly half the global warming emissions of coal combustion, while wind power, hydropower, and nuclear power produce only a few percent of emissions from coal combustion. The life cycle emissions of photovoltaics (PVs) are generally somewhat higher than those for wind power, hydropower, and nuclear power, because manufacture of PVs entails greater global warming emissions.[5]

The greenhouse gas emissions stemming from nuclear power depend greatly on the technology used to enrich uranium. The technology now used

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[5] Several analyses compare the emissions from different technologies for generating electricity. These include Scott W. White and Gerald L. Kulcinski, "Birth to death analysis of the energy payback ratio and CO_2 gas emission rates from coal, fission, wind, and DT fusion electrical power plants," Fusion Technology Institute, Department of Engineering Physics, University of Wisconsin-Madison, UWFDM-1063 (March 1998, revised February 1999), online at *http://fti.neep.wisc.edu/pdf/fdm1063.pdf*; and a comparable assessment of a photovoltaic system and a combined-cycle natural gas plant, Paul J. Meier, "Life-cycle assessments of electricity generation systems and applications for climate change policy analysis," University of Wisconsin-Madison, Ph.D. dissertation (August 2002), online at *http://fti.neep.wisc.edu/pdf/fdm1181.pdf.*

See also Luc Gagnon, Camille Belanger, and Yohji Uchiyama, "Life-cycle assessment of electricity generation options: The status of research in year 2001," *Energy Policy* 30 (2002):1267–1278; Central Research Institute of Electric Power Industry, Japan, "Finding life cycle CO_2 emissions by power generation type," online at *http://criepi.denken.or.jp/en/e_publication/home338/index.html;* Centre for Integrated Sustainability Analysis, University of Sydney, "Life-cycle energy balance and greenhouse gas emissions of nuclear energy in Australia," (November 2006), online at *http://www.pmc.gov.au/umpner/docs/commissioned/ISA_report.pdf;* and Joseph V. Spadaro, Lucille Langlois, and Bruce Hamilton, "Assessing the difference: Greenhouse gas emissions of electricity generation chains," *IAEA Bulletin* 42, 2 (2000):19–24, online at *http://www.iaea.org/Publications/Magazines/Bulletin/Bull422/article4.pdf.* See also U.K. Sustainable Development Commission, "The role of nuclear power in a low-carbon economy," Paper 2, "Reducing CO_2 emissions: Nuclear and the alternatives" (March 2006), online at *http://www.sd-commission.org.uk/publications/downloads/Nuclear-paper2-reducing*CO_2*emissions.pdf.*

in the United States—gaseous diffusion—requires a large amount of electricity: roughly 3.4 percent of the electricity generated by a typical U.S. reactor would be needed to enrich the uranium in the reactor's fuel.[6] Because fossil fuels generate 70 percent of U.S. electricity, emissions from that enrichment would account for some 2.5 percent of the emissions of an average U.S. fossil fuel plant. However, in the near future, U.S. uranium will be enriched using gaseous centrifuge technology, which consumes only 2.5 percent of the energy used by a diffusion plant. Thus this part of the nuclear power life cycle would result in very low emissions.[7]

Besides energy-related emissions, nuclear power is linked to two other sources of global warming emissions: cement manufacturing, which releases carbon dioxide, and the production of iron and steel, which releases carbon dioxide and methane.[8] While nuclear power plants contain a large amount of reinforced concrete, emissions from producing that concrete, allocated over the lifetime of the reactor, are insignificant compared with emissions from a fossil fuel plant.

The Future Role of Nuclear Power—and Its Risks

While nuclear reactors are now used to generate electricity, they could potentially also be used to produce hydrogen fuel for transportation. Reducing emissions in the electricity sector may also prove easier than in other sectors, providing an incentive to use electricity rather than other forms of energy.[9] For example, electric heat pumps rather than natural gas burners could be used to heat residential buildings, and electric vehicles could be used in place of gasoline-fueled ones.

For these reasons, an expansion of nuclear power both in the United States and around the world has been proposed as one response to global warming. While many different technologies will be needed to address climate change, the urgency of this situation demands that we be willing to consider all options.

Today 104 reactors produce some 20 percent of U.S. electricity. If demand for electricity in 2050 is roughly that of today—because energy conservation offsets increases in demand—another 100 reactors would be required to produce an additional 20 percent of U.S. electricity in 2050. Because electricity production contributes roughly a third of U.S. global warming emissions today, those additional 100 reactors would reduce emissions by 6–7 percent relative to today. Recall that to avoid dangerous climate change, the United States and other industrialized nations will need to reduce emissions at least 80 percent by mid-century, compared with 2000 levels (which are comparable to today's levels). Thus an additional 100 reactors would contribute roughly 8 percent of the total required U.S. reduction (6–7 percent of the required 80 percent), under the assumption that efficiency and conservation measures could offset any growth in electricity demand. (Without additional conservation and efficiency measures, U.S. electricity consumption is projected to almost double by 2050.)

All energy sources entail risks to the environment and human health. For example, the risks of carbon capture and storage—which would reduce the net global warming emissions from using fossil fuels to generate electricity—include gas explosions and the release of large amounts of previously stored carbon dioxide, which could undo previous emissions reductions. However, this report focuses on the risks of nuclear power and how to reduce them.

Nuclear power has significant and inherent risks that we must take into account when addressing global warming. These risks include a large release

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[6] Roughly 100,000–120,000 separative work units (SWUs) are required to enrich uranium for a year's worth of fuel for a typical 1,000 MWe light-water reactor, and gaseous diffusion requires roughly 2,400–2,500 kWh per SWU. (SWU is a measure of the amount of energy used to produce uranium of a specified enrichment level from a feedstock with an initial enrichment level, with the leftover uranium "tails" of a given enrichment level.) Thus, producing a year's worth of enriched uranium consumes up to 300,000 MWh of electricity, or roughly 3.4 percent of the electricity the reactor generates in a year.

[7] Gas centrifuge plants require only about 60 kWh/SWU. Louisiana Energy Services is building a gas centrifuge facility in New Mexico. See *http://www.nrc.gov/materials/fuel-cycle-fac/lesfacility.html*. The U.S. Enrichment Corp. is planning to build a similar facility in Ohio. See *http://www.usec.com/v2001_02/HTML/Aboutusec_Centrifuge.asp*.

[8] This is also the case for wind power, which uses steel turbines built on concrete pads.

[9] This would be particularly true for the distributed use of fossil fuels, which is incompatible with capturing and storing carbon.

of radiation from a power plant accident or terrorist attack, and the death of tens of thousands or more from the detonation of a nuclear weapon made with material obtained from a civilian nuclear power system. (This report will not consider the risks of dirty bombs, in which a conventional explosive is used to spread radiological material.) Unless fundamental changes are made in the way nuclear power is operated and controlled, a large-scale expansion of nuclear power in the United States—or worldwide—would almost certainly increase these risks.

Moreover, addressing the problems associated with nuclear power is simply pragmatic: nothing will affect public acceptability of nuclear power as much as a serious nuclear accident, a terrorist strike on a pool of spent fuel, or a terrorist detonation of a nuclear weapon made from stolen nuclear reactor materials.

The following four chapters discuss the risks associated with nuclear power—including reactor accidents, sabotage and terrorist attacks on nuclear plants, the acquisition of nuclear weapons materials by terrorists and nations, and radioactive waste—and make specific recommendations for how to minimize those risks. While focused on the U.S. situation, this analysis has broader relevance to improving nuclear safety and security worldwide. The final chapter reviews new types of nuclear plants proposed in the United States, and considers to what extent they will make performance safer, increase resistance to sabotage and attack, make nuclear terrorism and proliferation less likely, and improve the waste disposal process.

Chapter 2

Ensuring the Safety of Nuclear Power

An operating nuclear power plant contains a large amount of radioactive material, and an accident that results in the release of this material could cause significant harm to people and the environment. People exposed to high levels of radiation will die or suffer other health consequences within days or weeks. Lower radiation levels can cause cell damage that will eventually lead to cancer, which may not appear for years or even decades. People may need to be permanently evacuated from areas contaminated with radiation. The costs of evacuation and environmental remediation, and those of the loss of usable land, could be enormous. Radioactivity released by a severe accident could lead to the death of tens of thousands of people, injure many thousands of others, contaminate large areas of land, and cost billions of dollars.

One measure of safety problems is, of course, whether accidents do occur that release radioactivity and cause environmental contamination, or affect the health of workers or the public. The history of nuclear power, both in the United States and internationally, has been marred by such accidents.

The worst nuclear power accident the world has seen was the 1986 explosion and fire at the Chernobyl Unit 4 reactor in the Ukraine, and the resulting dispersal of radioactive material over western areas of the Soviet Union and much of Europe.[10] The accident contaminated a region of 10,000 square kilometers (half the size of New Jersey), and required the evacuation of more than 100,000 people and the permanent relocation of 220,000 people. The accident has resulted in roughly 4,000 cases of thyroid cancers in people who were children or in utero during the accident, and will cause an estimated 60,000 cancers and 40,000 cancer deaths overall.[11]

The second-worst nuclear power accident occurred in 1979 at the Three Mile Island site in Pennsylvania, where the reactor came very close to a total core meltdown; half of the core melted and part of it disintegrated. Fortunately, most of the radiation was contained despite a hydrogen

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[10] The Chernobyl reactor was a graphite-moderated channel reactor. These reactors have serious inherent safety vulnerabilities. They were built only in the Soviet Union, and have since been modified to reduce those vulnerabilities. Eleven such reactors remain in operation in Russia, and one in Lithuania.

[11] Radioactive iodine can concentrate in the thyroid, delivering high radiation doses to thyroid tissue and posing an elevated risk of thyroid cancer, particularly in children. See E. Cardis et al., "Risk of thyroid cancer after exposure to ^{131}I in childhood," *Journal of the National Cancer Institute* 97 (2005):724–732.

Perhaps the most authoritative report on the consequences of Chernobyl is *Chernobyl's legacy: Health, environmental and socio-economic impacts*, released by the UN-sponsored Chernobyl Forum (September 5, 2005). According to this report, "Claims have been made that tens or even hundreds of thousands of persons have died as a result of the accident. These claims are exaggerated: the total number of people that could have died or could die in the future due to Chernobyl originated exposure over the lifetime of emergency workers and residents of [the] most contaminated areas is estimated to be around 4,000." Online at *http://www.iaea.org/NewsCenter/Focus/Chernobyl/pdfs/05-28601_Chernobyl.pdf.*

However, by limiting its analysis to people with the greatest exposure to released radiation, the report seriously underestimates the number of cancers and cancer deaths attributable to Chernobyl. According to the 1993 report "Sources and effects of ionizing radiation" of the United Nations Scientific Committee on the Effects of Atomic Radiation, "The collective effective dose committed by this accident is estimated to have been about 600,000 man-Sv" (p. 23). (A sievert, or SV, is a measure of the radiation dose that takes into account the different biological effects of radiation on different types of tissue.)

Using data from Table ES-1 of the 2006 NAS report *Health risks from exposure to low levels of ionizing radiation: BEIR VII Phase 2* (Washington, DC, p. 15, *http://www.nap.edu/books/030909156X/html*), we see that the expected incidence and mortality of solid cancers and leukemia are 0.1135 cancer cases and 0.057 cancer deaths per Sv. For a collective dose of 600,000 person-Sv, the expected number of cancer cases would be 68,000, of which some 34,000 would result in death. Note that because exposure only increases the probability of contracting cancer, in general no given cancer can be attributed directly to Chernobyl. Moreover, because these additional cancers will be distributed among millions of people, they will not be discernable among all the other cancer cases. (Table ES-1 indicates that on average, 42 percent of people have cancer at some point in their lives, and about 20 percent of people die of cancer.) However, the large increase in thyroid cancers among children in Belarus, Ukraine, and Russia following the accident clearly indicates that it was the cause of the increase.

explosion that raised the pressure inside the containment vessel by a factor of 10. Facilities for producing materials for nuclear weapons have also seen two serious accidents. Both occurred in 1957, one at the Mayak reprocessing plant in the Soviet Union, and one at the Windscale Pile in England.

Nuclear power plants have experienced scores of more minor accidents and near-misses. These include an accident in Japan in December 1995, when the Monju reactor leaked sodium coolant, setting off a serious fire. Sodium burns fiercely when in contact with air and reacts violently when added to water, making it difficult to control.

A recent example of a near-miss is the 2002 discovery that the Davis-Besse reactor in Ohio had a sizable hole in its head: only a thin skin of stainless steel kept radioactive materials from spreading within the plant. Continued operation for a few more months would have led to a Three Mile Island-style core meltdown, or worse (see Box 1).[12] In fact, the Nuclear Regulatory Commission (NRC) has reported four dozen "abnormal occurrences" to Congress since 1986, and notified the International Atomic Energy Agency of 18 nuclear "events" since reporting began in 1992.[13]

While no technology can be perfectly safe, nuclear power is an inherently risky technology, and minimizing its risks requires stringent safety standards and practices. The United States has relatively strong safety *standards* for nuclear power. However, serious safety problems continue to arise because the NRC does not adequately *enforce* those standards.

Of course, accidents are not the only measure of safety, and the absence of accidents does not necessarily indicate that there are no safety problems. The number of U.S. reactors shut down for a year or longer to address numerous safety problems provides strong evidence of poor safety practices and inadequate NRC enforcement. A weak "safety culture" within the NRC itself prevents effective oversight. The agency also relies on flawed approaches to assessing risks and inspecting nuclear facilities, and its standards for preventing and mitigating severe accidents are too low.

The NRC has recently taken steps to limit public participation in the reactor licensing process, even though past participation has led to improved safety. Moreover, rather than raising the bar for new reactor designs, the NRC is relying on existing standards, and federal limits on the liability of nuclear plant owners reduce incentives to improve the safety of future reactors. The NRC also suffers from an inadequate budget. These shortcomings indicate that the NRC needs to greatly strengthen its approach to nuclear power safety.

The Role of the NRC

The NRC grants construction and operating licenses for commercial nuclear plants; sets safety and security standards for those plants, fuel-cycle facilities, and other facilities such as hospitals that process or use nuclear materials; conducts inspections; and imposes fines on plants not in compliance and requires owners to correct the deviations or shut down. Four times each year, the NRC assesses the safety performance of each nuclear plant in some 20 discrete categories, and makes these "report cards" available on its website.[14]

In the past, to build and run a reactor, utilities had to apply for a construction permit and then an operating license.[15] This procedure has been streamlined: new U.S. reactors will now receive a combined operating license.[16] In this procedure,

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[12] John Mangels and John Funk, "Davis-Besse could have blown top in 60 days," *Cleveland Plain Dealer*, May 5, 2004.

[13] The International Atomic Energy Agency uses the International Nuclear Events Scale to rate the severity of an "event" according to the amount of radioactivity released onsite and offsite, damage to the reactor core and radiological barriers, and the extent to which defense-in-depth is degraded. See International Atomic Energy Agency, *The international nuclear event scale (INES) user's manual*, 2001 edition (Vienna), online at *http://www-news.iaea.org/news/inesmanual/INES2001.pdf.*

Defense-in-depth is one of the main means of ensuring nuclear power safety. It entails having multiple layers of redundant and independent safety systems, so failure of a critical component will not cause a core meltdown or other failure of reactor containment.

[14] The report cards and information on how the performance ratings are determined are online at *http://www.nrc.gov/NRR/OVERSIGHT/ASSESS/index.html.*

[15] The regulations are in 10 CFR Part 50, online at *http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/.*

[16] The new regulations are in 10 CFR Part 52, online at *http://www.nrc.gov/reading-rm/doc-collections/cfr/part052/part052-0003.html.*

Box 1. Near-Miss at Davis-Besse

The Davis-Besse reactor in Ohio is a stunning example of how problems with the NRC's safety culture have put the public at risk.[17] In fall 2001, NRC staff members analyzed conditions at Davis-Besse, and were so concerned that they drafted an order requiring the reactor to shut down for immediate inspection of parts they suspected were cracked and potentially leaking reactor cooling water. Cracks and leaks had been discovered in similar nuclear plants, such as Oconee in South Carolina, and NRC staff determined that Davis-Besse was highly vulnerable to the same degradation. But NRC managers ignored these safety concerns in favor of the economic pleas of the plant owner, and allowed the reactor to continue operating. The NRC's inspector general later found:

> *The fact that FENOC* [FirstEnergy Nuclear Operating Co., the reactor's owner] *sought and staff allowed Davis-Besse to operate past December 31, 2001, without performing these inspections was driven in large part by a desire to lessen the financial impact on FENOC that would result from an early shutdown.*[18]

Yet at the same time that NRC managers opted to protect the company's financial interests, they assessed whether Davis-Besse was meeting five safety principles, and found it was likely not meeting any of them.[19] In other words, the NRC had ample reason to suspect that disaster was looming at Davis-Besse.

When deferred inspections were finally conducted in March 2002, they revealed that all five safety principles had in fact been violated.[20] Cooling water had indeed leaked—most likely beginning in 1995, and this leakage had corroded a large hole through the reactor vessel's head. Only a thin stainless steel veneer—less than one-quarter-inch thick—had prevented a loss-of-coolant accident more serious than that at Three Mile Island in 1979. Had the corroded reactor vessel head ruptured, the loss of cooling water would likely have led to both a reactor meltdown and a containment failure. Davis-Besse was designed for a loss-of-coolant accident, but its two key backup systems were seriously impaired. The debris created by fluid jetting through a ruptured vessel head would likely have blocked and disabled the pumps needed to cool the reactor core and containment, triggering a reactor meltdown and failure of the containment barrier. Before restarting Davis-Besse, the plant owner had to fix both of the backup safety systems and replace the damaged reactor vessel head.

Researchers at Oak Ridge National Laboratory later evaluated how close Davis-Besse had come to disaster, and concluded that the best estimate was 230 days and a conservative estimate was 150 days.[21] Luck, not regulatory prowess, prevented that disaster from occurring.[22]

The NRC's abysmal performance in this case is especially troubling because its staff will likely never assemble a stronger case for a pending disaster than it did for Davis-Besse, yet NRC management chose to overlook public health concerns to protect the owner's financial interests. If the warning signs at Davis-Besse were not compelling enough to spur prompt action to protect public health, it is difficult to envision warning signs that would.

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[17] For details about the incident see Union of Concerned Scientists, "Davis-Besse: The reactor with a hole in its head", online at *http://www.ucsusa.org/assets/documents/clean_energy/ACFNx8tzc.pdf* .

[18] NRC, Office of the Inspector General, "NRC's regulation of Davis-Besse regarding damage to the reactor vessel head," Case No. 02-03S (December 30, 2002), online at *http://www.nrc.gov/reading-rm/doc-collections/insp-gen/2003/02-03s.pdf.*

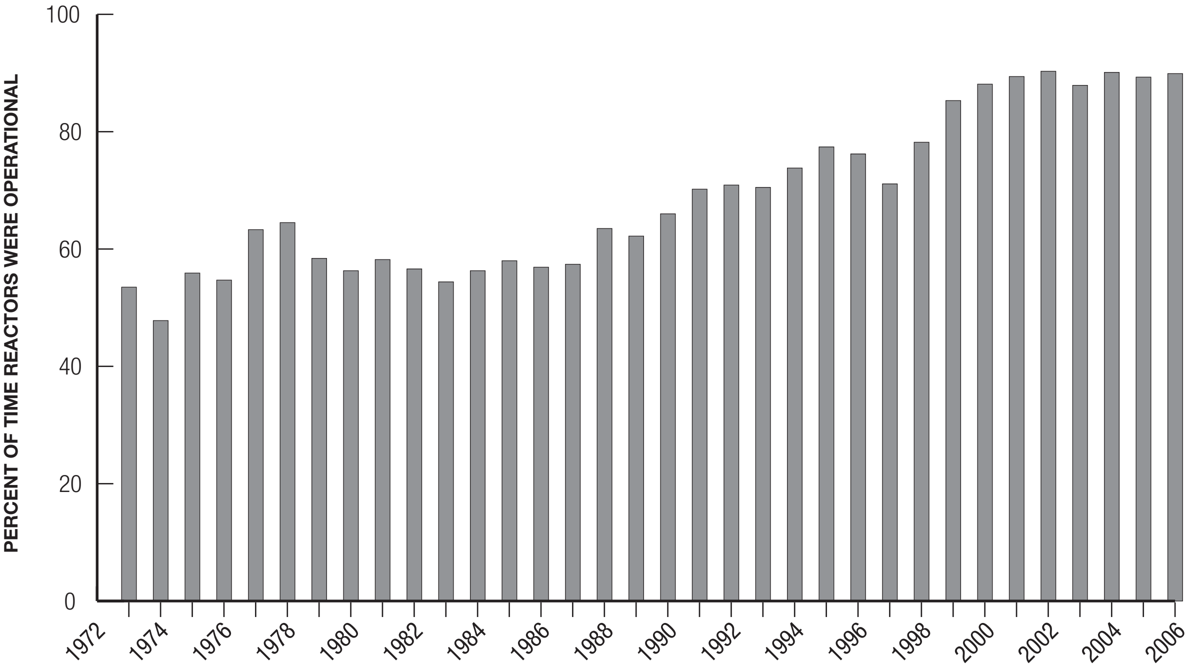
[19] NRC, presentation slides for staff briefing to executive director for operations, "Status of NRC staff review of FENOC's Bulletin 2001–01 Response for Davis-Besse" (November 29, 2001). The five safety principles were whether (1) current regulations are met; (2) the defense-in-depth philosophy is maintained; (3) sufficient safety margins are maintained; (4) the result is only a small increase in core damage frequency; and (5) performance measurement strategies are used to measure risk.

[20] The findings were: (1) the plant's operating license and federal regulations were not met; (2) one safety barrier had been lost; (3) safety margins had been significantly reduced; (4) core damage frequency rose significantly; and (5) discovery did not occur until the deferred safety inspections were performed. See J.E. Dyer, letter to Lew Myers, chief operating officer, FirstEnergy Nuclear Operating Co., "Final significance determination for a red finding, NRC Inspection Report 50-346/2003-16, Davis-Besse control rod drive mechanism penetration cracking and reactor pressure vessel head degradation" (May 29, 2003). Dyer was a regional administrator for the NRC.

[21] P. T. Williams, S. Yin, and B.R. Bass, "Probabilistic structural mechanics analysis of the degraded Davis-Besse RPV head" (Oak Ridge, TN, September 2004).

[22] Paul Gunter, Nuclear Information and Resource Service, and David Lochbaum, Union of Concerned Scientists, "Anatomy of a flawed decision: NRC has a brain, but no spine" (August 5, 2002), online at *http://www.ucsusa.org/clean_energy/nuclear_safety/nrcs-mistake-at-davis-besse.html.*

Figure 5. Average Annual Capacity Factor of U.S. Nuclear Power Reactors



Source: Energy Information Administration, "Annual Energy Review 2006," Table 9.2, p. 273, *http://www.eia.doe.gov/emeu/aer/pdflaer.pdf.*
Note: Data first became available in 1973. The dip in 1997 reflects the shutdown of six reactors in 1996 for safety reasons. These reactors remained shut down for a year or more.

a reactor vendor would ask the NRC to certify a standard design. If an operator applied for a combined operating license for a certified reactor, the NRC would need to assess only whether the design was appropriate for the intended site. If the operator did not use a certified standard design, the NRC would need to determine that both the reactor design and the proposed site were acceptable, which would take more time.

The NRC is a fee-based agency. Each year, the NRC prepares a budget for its oversight operations, which it submits to Congress for approval. Once the overall budget is approved, the NRC sets the annual license fee for each nuclear reactor by allocating this amount equally among the licensees. For example, the annual fee for each operating reactor was $3.7 million in 2006. When plant owners require NRC services beyond routine oversight, such as for reviewing and approving requests to operate a plant at higher power levels, the NRC charges an hourly rate. In 2006, the hourly rate for additional services was $217.[23]

Safety Problems: Year-plus Reactor Shutdowns

Operators shut down power reactors for many reasons: to refuel them, to conduct maintenance that cannot be done while the reactors are operating, to repair or replace large components, and to address safety problems. When a plant shuts down, it produces no revenue, so plant owners have a strong incentive to minimize shutdowns. The average percent of time that U.S. power plants are shut down each year has fallen dramatically over the past two decades: the capacity factor of U.S. reactors—the percent of time a reactor is operating—averaged 58 percent in the 1980s, 74 percent in the 1990s, and 89 percent from 2000 through 2006 (see Figure 5).

Several factors have contributed to this rising capacity factor. The time it takes to refuel reactors has declined. Since 1988, operators have been allowed to test the reliability of safety components while a plant is operating, instead of shutting it down for such tests. All U.S. reactors have now undergone the initial shakedown period when

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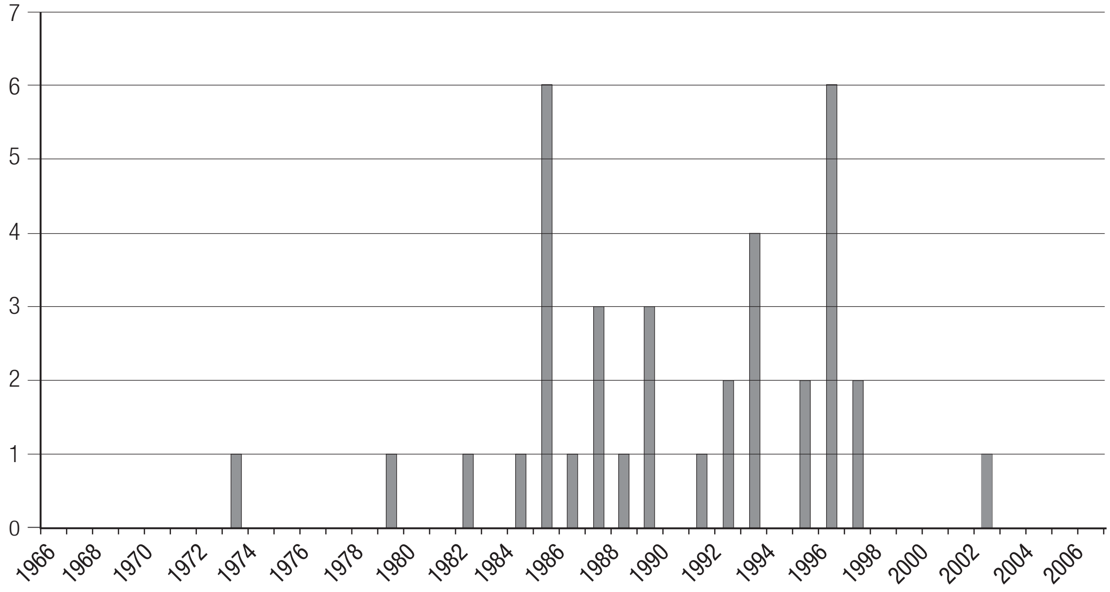
[23] Nuclear Regulatory Commission, "NRC publishes licensing, inspection, and annual fees for fiscal fear 2006," news release No. 06-073 (May 30, 2006), online at *http://www.nrc.gov/reading-rm/doc-collections/news/2006/06-073.html.*

Figure 6. Year-plus Reactor Outages



Source: David Lochbaum, *Walking a nuclear tightrope: Unlearned lessons of year-plus reactor outages* (Cambridge, MA: Union of Concerned Scientists, 2006).

operators identify and fix unexpected problems.

However, capacity factors are not a good indicator of plant safety, as they reflect only the *average* amount of time that a reactor is shut down. One reactor owner may aggressively search for safety problems and shut down a reactor to fix any problems as they arise, while another owner might fail to identify safety problems, ignore those that have been found, or defer addressing them, which could ultimately require a long shutdown. The average capacity factor of these two reactors might be identical, but the safety practices at the first are clearly superior to those at the second.

Thus, a particularly useful measure of nuclear power safety practices is the *duration* of shutdowns used to address safety problems. A recent Union of Concerned Scientists (UCS) report found 36 instances since 1979 in which the NRC shut down reactors to restore minimal safety standards and the owner took a year or more to address dozens or even hundreds of accumulated equipment problems (see Figure 6).[24] The most recent such instance was the 2002 outage at the Davis-Besse plant in Ohio, which remained shut down for almost two years. Had these relatively minor problems been addressed in a timely fashion, this extensive shutdown could have been avoided.

Case studies of year-plus outages developed for this report found commendable NRC behavior, such as with the Turkey Point Unit 3 outage in 1981, the Nine Mile Point Unit 1 outage in 1982, and the Sequoyah Units 1 and 2 outages in 1985.[25] In these cases, the NRC compelled reactor operators to resolve safety problems in a timely manner. The NRC's worst performance occurred in conjunction with the 1984 outage at San Onofre Unit 1 in California, the 1993 outage at Indian Point Unit 3 in New York, the 1996 outages at Millstone Units 2 and 3 in Connecticut, and the 2002 outage at Davis-Besse in Ohio. In these cases, the NRC allowed reactors with known safety problems to continue operating for months, sometimes

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[24] David Lochbaum, *Walking a nuclear tightrope: Unlearned lessons of year-plus reactor outages*, (Cambridge, MA: Union of Concerned Scientists, 2006), online at *http://www.ucsusa.org/assets/documents/clean_energy/nuclear_tightrope_report-highres.pdf.* The report found a total of 51 year-plus shutdowns at 41 of the 132 nuclear power reactors licensed in the United States since 1959. Four of the year-plus outages were needed to repair damage from an accident, such as the 1966 partial core meltdown at Fermi Unit 1 in Illinois and the 1975 fire at Browns Ferry in Alabama. Another 11 involved the repair or replacement of a single large component, such as the steam generator at Turkey Point Florida and recirculation piping at Pilgrim in Massachusetts. The remaining 36 outages occurred to restore safety levels. Two reactors were shut down twice to restore safety levels: the Davis-Besse plant in Ohio in 1985 and 2002, and the Sequoyah Unit 1 in Tennessee in 1985 and 1993.

[25] Case studies for the 51 year-plus reactor outages are available online at *http://www.ucsusa.org/clean_energy/nuclear_safety/unlearned-lessons-from.html.*

years, without requiring owners to fix the problems. On balance, these year-plus shutdowns indicate that the NRC has been doing a poor job of regulating the safety of power reactors. An effective regulator would be neither unaware nor passively tolerant of safety problems so extensive that a year or more is needed to fix them.

The NRC's Poor Safety Culture

According to the NRC, the safety culture of a nuclear plant reflects the willingness of its staff to raise and document safety issues, resolve these issues promptly, make "conservative" decisions, and conduct "probing" self-assessments. However, the NRC itself lacks a strong safety culture, and that is the most significant barrier to improving nuclear power oversight.

The NRC will not permit a nuclear reactor to run if it believes the staff operates in a poor safety culture. The NRC usually requires plant owners to take remedial steps when surveys find that 10 percent or more of workers in a department are reluctant to raise safety concerns. The NRC did not permit the Millstone and Davis-Besse reactors to restart until their safety cultures had been restored to acceptable levels. At the time, some 20 percent and 15 percent of the work force, respectively, was reluctant to raise safety concerns.[26]

Yet the NRC has failed to remedy problems with its own safety culture. For example, in a 2002 survey by the agency's Office of the Inspector General, nearly 50 percent of NRC staffers reported feeling unable to raise concerns about safety at nuclear power plants without fear of retaliation.[27] In the inspector general's 2005 survey, this unease remained a significant problem.[28] Since 2002, the NRC and Congress have focused on how to better manage safety culture at nuclear plant sites but have paid little attention to the poor safety culture afflicting the NRC. In fact, the NRC has stopped conducting surveys of its own staff and making the results available.[29]

These assessments of the NRC safety culture are consistent with the calls UCS has received from NRC staffers. We have heard numerous accounts of NRC managers instructing inspectors not to find any safety problems during upcoming visits to nuclear plants, telling inspectors not to write up safety problems that they do find, and ignoring the written objections of the agency's own experts when making safety decisions.[30]

Failure to Implement NRC Findings

One manifestation of the NRC's poor safety culture is its failure to implement its own findings on how to avoid safety problems. The 2002 near-miss of a reactor meltdown and containment breach at the Davis-Besse nuclear plant in Ohio provides a striking example. After this regulatory breakdown, the NRC tabulated lessons from regulatory breakdowns that led to year-plus outages at Indian Point (2000), Millstone (1997), and South Texas Project (1995) that had not yet been implemented.[31] The agency concluded that its failure to implement these lessons contributed to the Davis-Besse breakdown. One such lesson was not to rely too heavily on unverified commitments by plant owners to take specific steps. Yet as of January 2005, more than two years after Davis-Besse, the NRC had not yet implemented nearly 25 percent of the "high-priority" lessons from that incident.[32] (All but one of the 49 recommendations have since been implemented.)

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[26] Northeast Utilities presentation to the NRC, "Progress at Millstone Station" (December 12, 1997); and results of the FirstEnergy safety culture survey, January 2002 (available from the Union of Concerned Scientists).

[27] NRC, Office of the Inspector General, "OIG 2002 survey of NRC's safety culture and climate," OIG-03-A-03 (December 11, 2002), online at *http://www.nrc.gov/reading-rm/doc-collections/insp-gen/2003/03a-03.pdf.*

[28] NRC Office of the Inspector General, "2005 NRC safety culture and climate survey," executive summary, OIG-06-A-08 (February 10, 2006), online at *http://adamswebsearch2.nrc.gov/idmws/doccontent.dll?library=PU_ADAMS^PBNTAD01&ID=060440041.*

[29] NRC, Office of the Inspector General, "Special Evaluation: OIG 2002 Survey of NRC's Safety Culture and Climate," OIG-03-A-03 (December 11, 2002), online at *http://www.nrc.gov/reading-rm/doc-collections/insp-gen/2003/03a-03.pdf;* presentation by Little Harbor Consultants to NRC, "Update on LHC oversight activities at Millstone" (July 22, 1997); letter from FirstEnergy Nuclear Operating Co. to NRC, "Submittal of the Report Titled 'Safety Culture Evaluation of the Davis-Besse Nuclear Power Station,' dated April 14, 2003," online at *http://www.ucsusa.org/clean_energy/nuclear_safety/nrcs-mistake-at-davis-besse.html.*

[30] Letter from David Lochbaum, Union of Concerned Scientists, to NRC Chair Nils Diaz, "Kudos and mea culpa on safety conscious work environment" (February 2, 2004).

[31] NRC Lessons Learned Task Force, *Degradation of the Davis-Besse nuclear power station reactor pressure vessel head lessons-learned report*, Appendix F (September 2002).

[32] NRC internal memo from J. E. Dyer, director, Office of Nuclear Reactor Regulation, to Luis A. Reyes, executive director for operations, *Semiannual report: Status of implementation of Davis-Besse Lessons Learned Task Force report recommendations* (February 22, 2005).

FAILURE TO ENFORCE NRC REGULATIONS

Another symptom of the NRC's poor safety culture is its failure to enforce its own regulations, with the result that safety problems have remained unresolved for years at reactors that have continued to operate.

One example is the Hope Creek nuclear plant in New Jersey.[33] In 1996, the NRC fined PSEG, Hope Creek's owner, $150,000 for failing to properly maintain and test the system for driving the control rods. This system functions as the "brakes" on the reactor core, shutting down the nuclear chain reaction during both routine and emergency situations. PSEG did not fix the problem, and the NRC again fined the company for the same problem in 1998. PSEG still did not fix the problems but continued to operate Hope Creek. In 2004 an industry team brought in by PSEG concluded that "staff and management do not always demonstrate a healthy respect for reactor core reactivity," and noted "a number of significant reactivity vulnerabilities overall."[34] Finally, in fall 2005, PSEG extended an outage to resolve some of the problems with the drive system.

A second example of the NRC tolerating known safety violations is the Shearon Harris nuclear plant in North Carolina. Beginning in 1997 and regularly thereafter, NRC inspectors found non-compliances with fire protection regulations at the plant. After eight futile years of trying to restore compliance, the company informed the NRC in 2005 that it would give up that effort and instead attempt to bring the plant into compliance with alternate fire protection regulations the NRC had adopted in 2004. The company informed the agency that it might be able to meet these alternate regulations in 2009—12 years after the NRC first documented that Harris was in violation.[35]

GREATER EMPHASIS ON SCHEDULE THAN SAFETY

Another indication of the NRC's poor safety culture is its inappropriate emphasis on maintaining arbitrary schedules rather than safety. The NRC made adherence to schedules its foremost priority in June 1998, in response to a threat from the Senate Appropriations Committee to slash the agency's budget by nearly 40 percent. The NRC agreed to establish and meet timeliness goals for responding to business requests from operators (such as to increase the maximum power levels of reactors, or to reduce the frequency of safety checks), and to submit monthly progress reports to Congress. Those reports are now submitted quarterly, but the emphasis on timely resolution of business matters persists.

To meet these goals, the NRC reallocated its personnel from oversight of safety and security of nuclear plants to business matters. For example, within months of the Senate's budget threat, the NRC terminated its program to test security measures at nuclear power plants, citing budget constraints.[36] Public outcry forced the agency to reinstate these vital security tests.

The NRC then reduced the number of safety inspectors. For decades, the NRC had assigned full-time resident inspectors to nuclear plant sites using an N+1 approach: if a site had N operating reactors, it had a minimum of N+1 resident inspectors. The NRC then modified this rule by dropping the number of resident inspectors to N—but only for sites with two or more operating reactors.[37] However, the NRC failed to uphold this modified rule by maintaining just one inspector at Davis-Besse, which is a single reactor. This inspector shortfall contributed to the near-disaster at Davis-Besse, according to the Lessons Learned Task Force chartered by the NRC. That task force determined that "In the late 1990s, the NRC did

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[33] David Lochbaum, letter to A. Randolph Blough of the NRC, "Safety culture problems at the Salem and Hope Creek generating stations" (Union of Concerned Scientists, June 9, 2004), online at *http://ucsusa.org/clean_energy/nuclear_safety/page.cfm?pageID=1426.*

[34] Utility Services Alliance, "Salem/Hope Creek safety culture assessment" (March 1–5, 2004).

[35] Petition submitted by attorney John D. Runkle on behalf of NC Waste Awareness and Reduction Network, Nuclear Information and Resource Service, Union of Concerned Scientists, NC Fair Share, and Students United for a Responsible Global Environment (September 20, 2006), online at *http://www.ncwarn.org/Programs/ReactorSafety/default.htm.*

[36] Frank Clifford, "U.S. drops anti-terrorist tests at nuclear plants," *Los Angeles Times*, November 3, 1998.

[37] William D. Travers, NRC executive director for operations, to commissioners, "N+1 Resident Inspector Staffing Policy," SECY-99-227 (September 13, 1999), online at *http://www.nrc.gov/reading-rm/doc-collections/commission/secys/1999/secy1999-227/1999-227scy.html.*

not maintain the normal staffing levels within the regional branch that had regulatory oversight for DBNPS [David-Besse Nuclear Power Station].” The task force also concluded that “For the approximate one-year period from November 1998 to October 1999, there was only one resident inspector at DBNPS.”[38]

The February 2000 rupture of the steam generator tube at Indian Point in New York, which prompted a shutdown of the reactor, provides another example of an inappropriate NRC focus on schedules rather than safety. This tube rupture was serious, garnering the first red finding in the NRC’s four-level risk tier, with red being the most severe. Plant workers had identified this tube in 1997 as having degradation that exceeded federal limits, but this finding was misinterpreted and its significance overlooked. The next scheduled inspection was in 1999, but the owner asked the NRC to defer the inspection. The NRC staffer reviewing the deferral request found it lacking and asked follow-up questions. The NRC staffer was not satisfied, but was dissuaded from asking a second round of questions by an internal NRC procedure that read:[39]

> *When an RAI* [request for additional information] *is necessary, the staff should make every effort to limit itself to one round of RAIs per* [issue] *for an amendment application. The established timeliness goals are likely to be exceeded if multiple RAIs are needed to complete the staff’s review of a license amendment application.*

The NRC approved the deferral without asking any more questions. The Indian Point tube rupture occurred before the deferred inspection was to take place.

The NRC has required owners to correct poor safety culture at nuclear plants such as Millstone, Davis-Besse, South Texas Project, and Point Beach, and in each case the owners brought in managers from outside the company to stimulate needed reforms. The agency similarly needs to bring in outside managers to ensure needed reform of its own safety culture.

Recommendation:
To ensure that the NRC develops and sustains a strong safety culture as soon as possible, Congress should require the NRC to bring in managers—from outside the agency—charged with establishing such a culture, and evaluate them on whether they do so. Those efforts should focus on ensuring that the agency enforces its own regulations.

Flawed Approach to Assessing the Risks of Generic Safety Issues

When an actual or potential safety problem affects—or could affect—more than a single nuclear plant, the NRC labels it a generic safety issue, and, until it is resolved, treats it separately from safety problems that are unique to individual plants. That is, during this period, the NRC assesses the risk associated with the generic safety issue by assuming that all other plant systems are fully functional and reliable. It also assesses the safety risk at individual reactors by assuming that the generic safety problem does not exist.[40]

The NRC usually has 6 to 10 generic safety issues open at any given time, and often takes more than a decade to rectify these problems. In the interim, these unresolved safety issues may increase the likelihood of an accident, or worsen its consequences. Yet the NRC’s approach prevents it from accurately assessing the overall risk from an unresolved generic safety issue that occurs along with another safety problem.

A long-standing generic safety problem related to the emergency pumps of U.S. pressurized-water reactors (PWRs), a type of light-water reactor,

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[38] Arthur T. Howell III, NRC team leader, Davis-Besse Lessons-Learned Task Force, to William F. Kane, NRC deputy executive director for reactor programs, “Degradation of the Davis-Besse nuclear power station reactor pressure vessel head lessons learned report” (September 30, 2002).

[39] NRC, Office of the Inspector General, “NRC’s response to the February 15, 2000, steam generator tube rupture at Indian Point Unit 2 power plant” (August 29, 2000).

[40] See David Lochbaum, *U.S. nuclear plants in the 21st century: The risk of a lifetime*, Chapter 3 (Union of Concerned Scientists, May 2004), p. 13, online at *http://ucsusa.org/clean_energy/nuclear_safety/page.cfm?pageID=1408.*

illustrates the folly of this approach.[41] In 1979, the NRC determined that steam and water flowing through a broken pipe during an accident could dislodge pipe insulation and equipment coatings, which could clog the emergency pumps needed to cool the reactor core. The NRC closed this issue in 1985 without requiring any operating PWR to fix, or even assess, the problem. (It did require new reactors to address the safety problem before operating.) In 1996, the NRC reopened the issue after several nuclear plants in the United States and abroad actually experienced clogged emergency pumps, as forecast nearly two decades earlier. Fortunately, none of these situations occurred under accident conditions, where the consequences could have been catastrophic.

In 2001, the owner of the Oconee nuclear plant in South Carolina notified the NRC that it had discovered cracked and leaking pipes—harbingers of the scenario in which debris could block emergency pumps during an accident. This problem affected 69 operating U.S. power reactors. Yet the NRC analyzed the emergency pump problem by assuming that there was a very low probability that a pipe would crack, and analyzed the problem of cracked and leaking pipes by assuming a very low probability that the emergency pump would fail. Thus the NRC allowed the Oconee reactor to continue operating without resolving how to prevent debris from blocking the emergency pumps, despite knowing that the reactor had cracked pipes that could produce such debris.

This flawed decision making contributed to the near-disaster at Davis-Besse, a sister plant of Oconee. Of the plants afflicted with cracked and leaking pipes, the NRC staff determined Davis-Besse to be the most vulnerable, and drafted an order requiring the plant to shut down. However, NRC managers decided not to issue the order, largely based on the ability of emergency pumps to respond in the event that cracked pipes triggered an accident. When Davis-Besse shut down for refuelling, workers found significant damage to the reactor vessel head from the cracked pipes and significant impairment of the emergency pumps. By evaluating these two risks in isolation, the NRC underestimated the overall risk of continuing to operate the reactor.

Recommendation:

The NRC should treat generic safety issues on par with those found at single reactors. Until a generic issue is resolved, the NRC should fully account for it as a potential risk factor by integrating it into its safety analyses and decision making.

Flawed Inspection Methodology

To ensure that reactors are operated and maintained as required by federal regulations, the NRC conducts periodic inspections and tests safety equipment. However, NRC inspection methodology is flawed, and has allowed safety problems to go undetected for decades. The flaws are twofold: the inspections are too limited in scope, and the inspection techniques are not varied enough to detect problems with aging equipment that is slowly deteriorating.

Monitoring every inch of a nuclear plant is impractical. The NRC therefore targets equipment and structures considered most vulnerable to degradation, under the theory that problems will appear there first. When degradation is discovered outside the scope of the inspection through other means, the scope is enlarged to include the suspect equipment or regions. However, the NRC does not conduct periodic inspections of non-targeted equipment and structures, which could either confirm that the scope boundaries are properly drawn or detect degradation before it manifests as a problem.

For example, at the Quad Cities nuclear plant in Illinois (January 2002) and the Oconee reactor in South Carolina (February 2001), safety equipment that was being routinely inspected

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[41] See David Lochbaum, "Regulatory malpractice: NRC's 'handling' of the PWR containment sump problem" (Union of Concerned Scientists, October 29, 2003), online at *http://www.ucsusa.org/clean_energy/nuclear_safety/page.cfm?pageID=1278.*

failed; the failures occurred in parts that were not being inspected.[42] At Quad Cities, workers were routinely inspecting the ends of brackets that hold components in the proper orientation within the reactor vessel. These inspections began in the 1980s after one end of a bracket broke at the Dresden plant in Illinois, Quad Cities' sister plant. Although multiple inspections at Quad Cities found no signs of cracking, a bracket broke in January 2002. The ends of the bracket were in fine shape, but the bracket—less than a foot long—broke in the middle. In this case and many like it, workers were using the right detectors but were looking in the wrong places.[43]

The defunct Big Rock Point plant in Michigan provides the quintessential example of the need for more effective inspections and testing.[44] The owner permanently closed Big Rock Point in August 1997 after 39 years of operation. As the plant was being dismantled, workers discovered that the backup emergency system needed to shut down the reactor core during an accident had been broken for the previous 13 years. Although the system's pumps, motors, and valves had been periodically tested, and its pipes had been frequently inspected, no one had detected that the main pipe was completed severed. The individual components had been tested and inspected, but no integrated test was conducted to check whether the entire system would perform as needed during an accident.

Aging equipment usually degrades for a period of time before it fails completely. Such degradation represents a growing challenge to the safety margins of the aging fleet of U.S. reactors, especially given flawed inspections. For example, the failure of a steam generator tube at Indian Point (February 2000) in New York, and the leak in the "hot leg" pipe connecting the reactor vessel to the steam generator at Summer (October 2000) in South Carolina, resulted from slowly deteriorating equipment.

At Indian Point, workers used a probe to detect cracks and other flaws in the thin metal steam generator tubes in 1997. However, the probe was not state of the art, and workers failed to detect a crack that exceeded federal safety limits. After the tube failed in 2000, workers were able to recheck the data and see evidence of the crack they had missed in 1997. At Summer, workers used a similar probe to look for cracks in the hot leg pipe in 1995, and failed to detect a crack in the weld. After the weld leaked in 2000, workers rechecked the data and found indications of the crack they had missed earlier.

In this case, workers were looking in the right places, but failed to detect degraded conditions because of limitations of the inspection equipment or methods.[45]

Recommendations:

The NRC should require the use of multiple techniques for inspecting aging high-risk equipment, to ensure that degradation will be detected and corrected.

The NRC should periodically inspect equipment outside the normal inspection scope, to determine whether the scope is appropriate and to correct the scope before safety margins are compromised.

Flawed Risk Analyses

The NRC and the nuclear industry use probabilistic risk assessments (PRAs) for a variety of purposes. PRAs are calculations first developed in the NRC's *Reactor Safety Study* of 1975 (a.k.a. the Rasmussen report).[46] For example, because inspecting every inch of piping in a nuclear reactor is not feasible, PRAs are used to determine which portions of pipe are at greatest risk of failure, or would cause the most damage if a failure occurred, and hence should receive priority.

PRAs are also used to assess the possibility that multiple safety systems might fail and cause a

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[42] NRC, "Quad Cities Nuclear Power Station," Special Inspection Report 50-254/02-03(DRS) (April 17, 2002).

[43] See David Lochbaum, *U.S. nuclear plants in the 21st century: The risk of a lifetime* (Cambridge, MA: Union of Concerned Scientists, May 2004), Chapter 4, p. 20, online at *http://ucsusa.org/clean_energy/nuclear_safety/page.cfm?pageID=1408.*

[44] Letter from Consumers Energy to the NRC, "Liquid poison tank discharge piping found severed during facility decommissioning" (August 6, 1998).

[45] See David Lochbaum, *U.S. nuclear plants in the 21st century: The risk of a lifetime* (Cambridge, MA: Union of Concerned Scientists, May 2004), Chapter 4, p. 20, online at *http://ucsusa.org/clean_energy/nuclear_safety/page.cfm?pageID=1408.*

[46] NRC, "Reactor safety study: An assessment of accident risks in U.S. commercial nuclear power plants," WASH-1400 (NUREG-75/014) (October 1975).

reactor meltdown. For example, when a safety problem is discovered, the NRC and the nuclear industry use PRAs to assess the risk that a specific accident (such as a pipe breaking or a power supply failing) would occur, and that safety systems would fail to cool the reactor core in the event of such an accident. (If the reactor core is not adequately cooled, the fuel will melt; the molten material can lead to a rupture of the reactor vessel, a breach of the containment structure, and a release of radioactivity into the environment.)

In 1995 the NRC decided to base its decisions on PRAs rather than safety regulations to the maximum extent possible.[47] Under this ruling, the NRC can allow reactors to continue operating while in violation of regulations when a risk study concludes that the probability of an accident is very low. For example, if regulations required periodic testing of a certain component, and this component—by mistake—had not been tested during the last inspection, regulations would require the owner to shut down the reactor for the overdue test. However, under the new rule, if the component had performed well during prior tests, and these tests confirmed that the backup system would function if needed, PRAs could support a decision to allow the reactor to continue to operate until the next planned shutdown.

Used appropriately, PRAs can be a valuable tool. However, the NRC, its inspector general and Advisory Committee on Reactor Safeguards (ACRS), the Government Accountability Office (GAO), and UCS have documented serious problems with the agency's risk assessments, including omission of key data, inconsistent assumptions and methodology, and inadequate quality standards.[48] The ACRS pointed out in 2003 that a survey of NRC staff found that "most staff interviewees believe that the reluctance of the industry to improve the scope and quality of the PRAs is a major impediment to the advancement of risk-informed regulation."[49]

A seriously flawed risk assessment was at the core of the NRC's 2001 decision to allow the Davis-Besse nuclear plant to continue operating for six weeks until a scheduled refueling outage, despite numerous safety problems and regulatory violations. A May 2004 GAO report concluded that the NRC's risk analysis for Davis-Besse was "poorly documented and inadequately understood by NRC staff," and that a proper risk analysis "would have provided clear guidance for prompt shutdown." The GAO also found that the risks from continued operation were likely "unacceptably large," and that the NRC's use of these risk assessments is "ill-defined."[50] The NRC has not yet resolved these documented problems.

Recommendation:
The NRC should correct the flaws in its probabilistic risk assessments (PRAs), and should suspend decision making on reactor safety based on those assessments until it does so.

Inadequate Standards for Protection against Severe Accidents

Today's generation of nuclear reactors was designed and licensed according to their ability to withstand "design-basis accidents." The worst such accident—as defined by the NRC—involves partial melting of the reactor core, but not rupture of the reactor vessel or breach or bypass of the containment building. Thus reactors that conform to the "design basis" may still be vulnerable to "beyond-design-basis"—or "severe"—accidents, in which substantial damage to the reactor core and failure of the containment building lead to large releases of radiation.

The NRC has no regulatory criteria governing the maximum acceptable risk of severe accidents.

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[47] NRC Final Policy Statement, "Use of probabilistic risk assessment methods in nuclear regulatory activities," *Federal Register*, August 16, 1995.

[48] See David Lochbaum, *Nuclear plant risk studies: Failing the grade* (Cambridge, MA: Union of Concerned Scientists, 2000), online at *http://ucsusa.org/clean_energy/nuclear_safety/page.cfm?pageID=181*.

[49] NRC, Advisory Committee on Reactor Safeguards, "Improvement of the Quality of Risk Information for Regulatory Decisionmaking," letter to Chairman Nils Diaz, May 16, 2003.

[50] U.S. General Accounting Office (GAO), "Nuclear regulation: NRC needs to more aggressively and comprehensively resolve issues related to the Davis-Besse Nuclear Power Plant's shutdown" (May 2004), online at *http://www.gao.gov/docsearch/abstract.php?rptno=GAO-04-415*.

However, in 1986, the agency ruled in its Severe Accident Policy Statement that the risk of such an accident—as determined by a PRA for each plant—was acceptably low for most operating plants, and that no regulatory changes were required.[51] Yet the uncertainties inherent in these PRAs are great. They may not identify or analyze important accident sequences, and many of the parameters they use, such as the failure frequency of a particular component, are not known with any certainty.

The NRC does require operators of plants found to be vulnerable to severe accidents to fix their shortcomings. However, they must do so only if a cost-benefit analysis shows that the financial benefit of a safety backfit—determined by assigning a dollar value to the number of projected cancer deaths that would result from a severe accident—outweighs the cost of fixing the problem.

Even when a fix is clearly cost-beneficial, the NRC does not always require the change. For example, a detailed analysis by Sandia National Laboratories recently showed that a class of pressurized-water reactors with "ice condenser" containments was highly vulnerable to containment failure from hydrogen explosions in the event of a total loss of electrical power. The remedy—installing more backup power supplies—was found to be cost-effective. However, in the face of industry pressure, the NRC backed away from requiring the added backup power.

Instead of imposing regulatory requirements, the NRC has dealt with the threat of severe accidents largely by encouraging the nuclear industry to develop guidelines that would help each plant owner manage such an accident. However, because these measures are voluntary, they are not thoroughly vetted by the NRC to determine whether they would be feasible or effective.

The NRC also argues that its emergency planning requirements would adequately protect the public in the event of a severe accident. The NRC requires planning for evacuation, and distribution of potassium iodide (to reduce the risk of thyroid cancer, especially in children), within an "emergency planning zone" extending 10 miles from a plant. However, if a severe accident occurred and the containment structure were breached, people inside the 10-mile zone would likely receive enough radiation to immediately threaten their lives, while people well outside the zone would be exposed to levels high enough to cause a significant risk of cancer.

These cancers could be kept to a minimum by expanding the emergency planning zone. For example, if a severe accident occurred, it would be important to administer potassium iodide to children more than 100 miles downwind.[52]

Recommendations:

The NRC should reassess the vulnerability of all existing reactors to severe accidents, fully taking into account the uncertainties inherent in PRAs.

The NRC should require plant owners to implement measures to mitigate severe accidents, including making plant modifications and adopting emergency operating procedures, and should enforce these regulations.

The NRC should modify its emergency planning requirements to ensure that everyone at risk—not just people within the arbitrary 10-mile emergency planning zone—will be protected in the event of a severe accident.

Weak Approach to the Safety of New Nuclear Reactors

In 1986 the NRC issued an Advanced Reactor Policy Statement holding that advanced reactors need provide only the same level of protection as today's generation of reactors.[53] The NRC is loath to require stronger safety standards for new reactors because that would imply that current reactors are not safe enough. Thus its insistence that today's plants are safe is an obstacle to developing safer ones.

The NRC regulates where new nuclear power plants may be built. It bases these regulations on limiting public exposure to radiation in the event

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[51] NRC Policy Statement, "Safety goals for the operations of nuclear power plants" (July 30, 1986).

[52] Edwin Lyman, *Chernobyl-on-the-Hudson? The health and environmental impacts of a terrorist attack at the Indian Point Nuclear Plant* (Tarrytown, NY: Riverkeeper, September 2004), p. 24.

[53] NRC, "Regulation of Advanced Nuclear Power Plants: Statement of Policy," 51 FR 24643 (July 8, 1986).

of a design-basis accident, but does not consider the impact of severe accidents. NRC siting regulations therefore do not take into account the consequences of a severe accident at a plant built in a densely populated area.

Recommendations:

To ensure that new nuclear plants are significantly safer than existing ones, the NRC should require that new reactors have features designed to prevent severe accidents, and to mitigate them should they occur. These design features should reduce reliance on operator interventions in the event of an accident, which are inherently less dependable than built-in measures.

When making decisions on siting new reactors, the NRC should give significant weight to the potential health, environmental, and economic consequences of a severe accident, taking into account the proximity of population centers, water supplies, and agricultural areas.

Restrictions on Public Participation

Public input on nuclear power plants has long played an important role in the NRC's licensing process. The NRC itself has identified numerous examples where public participation has led to enhanced safety levels. As members of the NRC's former Appeal Board observed in 1974:

> *Public participation in licensing proceedings not only can provide valuable assistance to the adjudicatory process, but on frequent occasions demonstrably has done so. It does no disservice to the diligence of either applicants generally or the regulatory staff to note that many of the substantial safety and environmental issues which have received the scrutiny of licensing boards and appeal boards were raised in the first instance by an intervenor.*[54]

Yet the NRC has recently withdrawn the public's right to request depositions and cross-examine witnesses during hearings on license renewals for existing plants and license applications for new plants. The attorneys general of five states formally opposed this change, but the agency adopted it anyway.[55]

Under the guise of post-9/11 security, the NRC has also removed a significant amount of information from the public domain, including basic licensing documents such as the Updated Final Safety Analysis Report and probabilistic risk assessments used to assess the safety vulnerabilities of a nuclear power plant. And the NRC has severely cut back the resources it devotes to compliance with the Freedom of Information Act, and appears to have no process for internal review of its decisions on disclosing documents to the public. Finally, the NRC continues to give the public no right to be heard regarding enforcement of its safety regulations, so public petitions on such enforcement tend to languish before the agency.

The NRC's actions have severely compromised the public's ability to advocate rigorous regulation of nuclear facilities, and to provide a counterweight to the industry's constant pressure to reduce government oversight. This should be a matter of serious concern to Congress and the public, given that the NRC faces significant regulatory challenges, including overseeing an aging fleet of reactors, issuing the first construction permits and operating licenses for new reactors since the Three Mile Island accident, and licensing new facilities that pose proliferation risks because they reprocess nuclear power plant fuel and handle plutonium.

Recommendations:

The NRC should fully restore the public's right to discovery and cross-examination before and during hearings on changes to existing licenses for nuclear power plants and applications for new ones, and fully fund its Freedom of Information Act office.

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[54] Gulf States Utility Corp. (River Bend Units 1 and 2), ALAB-183, 7 AEC 22, 227-28 (1974).

[55] Opinion of the United States Court of Appeals, First Circuit, *Citizens Awareness Network, Inc., and National Whistleblower Center et. al. v. United States of America and United States Nuclear Regulatory Commission* (No. 04-1145), December 10, 2004, online at *http://www.ca1.uscourts.gov/cgi-bin/getopn.pl?OPINION=04-1145.01A.*

The NRC's Budget Constraints

Despite the numerous problems noted above, Congress continues to pressure the NRC to cut budgets and streamline regulations rather than improve oversight. Indeed, except for a modest funding increase after 9/11 to handle new security demands, such as revising security rules and increasing the frequency of security inspections, the agency's budget and staffing levels have steadily declined since 1993. Until 1998 that decline seemed warranted, as the agency has not licensed a nuclear plant since 1996, and a number of plants have permanently closed. However, in 1999 budget constraints led the NRC to cut back on the number of inspectors assigned full-time to monitor operating nuclear power plants. Congress has also failed to account for the growing number of applications from owners to renew licenses for existing plants, and the agency's expanding efforts to evaluate designs for more advanced reactors.

As noted, the agency responded to these budget constraints by prioritizing timeliness over safety, which entailed reducing the number of inspectors at operating plants and cutting its overall inspection effort by more than 20 percent between 1993 and 2000. The inspection program has improved somewhat since 2001: the average number of inspection hours per plant site was 11 percent higher in 2005 than in 2001.[56] However, the NRC disbanded its Office for Analysis and Evaluation of Operational Data, an independent body that monitored power plant safety and assessed the effectiveness of NRC programs.

Recommendation:

Congress should ensure that the NRC has enough resources to provide robust oversight of nuclear reactor safety, and to meet its goals for responding to requests from reactor owners in a timely manner without compromising safety.

How the Price-Anderson Act Undermines Safety Incentives

Another barrier to improved safety measures and operating standards is the Price-Anderson Act, which was enacted in 1957 to provide liability protection for owners of nuclear power plants. The 2005 Energy Policy Act extended the Price-Anderson protections to reactors built during the next 20 years.

Today each owner must obtain at least $300 million in private insurance coverage for each nuclear reactor. If an accident results in larger losses, the owners of other nuclear reactors must contribute liability payouts of up to $100 million each, for a total of about $10.4 billion. Beyond that amount, the U.S. government would presumably establish a compensation fund to cover claims resulting from the accident, as it does for uninsured losses resulting from natural disasters.

The rationale for the act was that private industry could not afford to operate commercial nuclear power plants because of the unprecedented liability that could result from a catastrophic accident. For example, the *Wall Street Journal* reported that the cost of the 1986 Chernobyl accident significantly exceeded the total economic benefits accrued from the dozens of Soviet nuclear power reactors operating between 1954 and 1986.[57] In the United States, costs resulting from a large release of radiation from a damaged nuclear reactor or spent fuel pool could exceed $100 billion, surpassing the Price-Anderson limit by a factor of 10 or more.[58]

The Institute for Nuclear Power Operations, an organization created and funded by the nuclear industry, evaluates each plant periodically in areas such as operations, maintenance, engineering, radiation protection, and training, and insurers use the resulting ratings to set annual premiums. Safer, better-performing nuclear plants pay less than those with problems. However, in 2005, the average

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[56] NRC memo from Luis A. Reyes, executive director for operations, to the commissioners, "Reactor oversight process self-assessment for calendar year 2005," SECY-06-0074 (March 31, 2006).

[57] Richard L. Hudson, "Cost of Chernobyl nuclear disaster soars in new study," *Wall Street Journal*, March 29, 1990.

[58] J. Beyea, E. Lyman, and F. von Hippel, "Damages from a major release of ^{137}Cs into the atmosphere of the United States," *Science and Global Security* 12 (2004):125–136; and Edwin Lyman, *Chernobyl-on-the-Hudson? The health and economic impacts of a terrorist attack at the Indian Point Nuclear Plant* (Tarrytown, NY: Riverkeeper, September 2004).

annual insurance premium for a single-unit reactor site was $400,000.[59] That represented only 0.2 percent of the average annual operating cost of $205 million—a drop in the proverbial bucket.[60]

The Price-Anderson liability limit therefore serves as a disincentive for industry to develop and use additional safety features, or to adopt reactor designs that are safer but more expensive (see more on this in Chapter 6). Without Price-Anderson—or with a higher liability limit—the added cost of improved safety features would be offset by much lower annual premiums. This could occur if the average insurance premium represented, say, 20–50 percent of annual operating costs rather than 0.2 percent.

In recent congressional testimony, the vice president of General Atomics, which makes nuclear reactors, stated that its advanced high-temperature gas-cooled reactor will be so safe that it will not need Price-Anderson protection.[61] Aside from whether this particular design would significantly improve safety (again, see Chapter 6), today's liability policy should encourage all vendors to improve the safety of their reactors. Eliminating liability protection entirely would provide the strongest incentive for safety improvements, as well as end this government subsidy of nuclear power. However, this step is probably politically infeasible. Raising the liability limit may be a reasonable alternative, at least in the near term.

Recommendation:
Congress should eliminate Price-Anderson liability protection—or substantially raise the liability limit—for new U.S. nuclear power plants, to remove financial disincentives for vendors and owners to improve safety.

Improving International Safety Standards and Practices

The Chernobyl accident demonstrated that an unsafe reactor is a threat not only to its host country but also to neighboring countries and other nations far downwind. An accident anywhere in the world also prompts the public everywhere to lose confidence in the safety of nuclear power. Thus the viability of the nuclear industry—and of its potential role in addressing climate change—is held hostage to the industry's worst performers.

The gravity of this problem is underscored by the fact that although 33 different countries now operate more than 400 nuclear reactors, no international regulations ensure compliance with safety standards. While four legally binding conventions address nuclear safety, they are only "incentive instruments," and the International Atomic Energy Agency has no ability to sanction countries or owners for failing to comply.[62]

In the aftermath of Chernobyl, the World Association of Nuclear Operators (WANO) was formed to promote international exchange on "best practices" in nuclear safety. WANO arranges for "peer reviews" of nuclear plants around the world and monitors plant performance. However, WANO is not accountable to governments or the public, and it performs the bulk of its work out of public view. It is not a substitute for an international regulatory system with mechanisms for oversight and public participation. Ideally, an international nuclear regulatory body would oversee the performance of national regulatory agencies (such as the NRC) to ensure that national standards meet a uniform set of international safety standards, and that they are enforced. Such a body would have the authority to impose penalties for violations.

Recommendation:
The United States should work to establish an international regime with stringent, mandatory standards for nuclear safety and strong enforcement mechanisms.

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[59] NRC Fact Sheet, "Nuclear insurance: Price-Anderson Act" (May 2005), online at *http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/funds-fs.html.*

[60] "US nuclear operating costs push up above inflation in 2005," *Nucleonics Week* 47, 37 (September 14, 2006):1.

[61] Congressional testimony of Dr. David Baldwin, senior vice president, General Atomics, before Subcommittee on Energy And Resources, House Committee on Government Reform (June 29, 2005), online at *http://reform.house.gov/UploadedFiles/6.29.05%20Baldwin%20Testimony.pdf.*

[62] See *http://www.iaea.org/Publications/Documents/Conventions/index.html.*

Chapter 3

Defending against Sabotage and Terrorist Attacks

The 9/11 attacks highlighted the concern that nuclear plants, their onsite storage pools for spent fuel, and spent nuclear fuel being transferred between facilities for reprocessing or storage may be vulnerable to terrorist attacks that could cause significant radiation releases. Given the growing sophistication and adaptability of terrorist networks and the limited ability of governments to deal with them effectively, this risk will likely persist into the foreseeable future.

Recent independent studies have highlighted the vulnerability of commercial nuclear power plants to terrorist attack, and the possible consequences of such attacks. For example, a 2002 study by the National Academy of Sciences concluded that the near-term potential is high for civilian nuclear power plants to suffer from a ground or air assault as sophisticated as the 9/11 attacks.[63] The results could include a core meltdown and very large releases of radioactivity.[64]

Indeed, if a team of well-trained terrorists forcibly entered a nuclear power plant, within a matter of minutes it could do enough damage to cause a meltdown of the core and a failure of the containment structure. Such an attack would have a devastating and long-lasting impact on public health, the environment, and the economy.

The effects of such an attack would be particularly severe for a nuclear plant near a densely populated metropolitan area. A prime example is the dual-reactor Indian Point plant, which is 25 miles north of New York City. A 2004 study by an author of this report (Edwin Lyman) for the environmental group Riverkeeper found that a terrorist attack on one of the Indian Point reactors could result in up to 44,000 near-term deaths from acute radiation poisoning, 500,000 long-term deaths from cancer, widespread contamination in New Jersey and Connecticut, and economic damages exceeding $2 trillion.[65] The study assumed that the attackers damaged only the reactor and not the spent fuel pools, which also contain large quantities of radioactive material. To determine the maximum expected casualties, the study assumed that the attack was staged at night, when prevailing winds tend to blow from Indian Point toward New York City. (This is a well-known meteorological phenomenon that terrorists could exploit.) This study was performed using the same computer program and assumptions about the types and amounts of radiation released that the NRC itself uses in conducting accident assessments.[66]

While Indian Point is sited in the most densely populated area of any U.S. reactor, the danger of a highly destructive terrorist attack is not limited to Indian Point. U.S. census figures indicate that as

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[63] Committee on Science and Technology for Countering Terrorism, *Making the nation safer: The role of science and technology in countering terrorism* (Washington, DC: National Academy of Sciences, 2002), online at *http://www.nap.edu/books/0309084814/html.*

[64] Ibid, Table 2.1C, pp. 46–47.

[65] Edwin S. Lyman, *Chernobyl-on-the-Hudson? The health and economic impacts of a terrorist attack at the Indian Point Nuclear Plant* (Tarrytown, NY: Riverkeeper, September 2004). The consequences would be worse than those for the Chernobyl accident because a severe accident in a light-water reactor would be less energetic, and thus tend to deposit more radioactive material closer to the reactor site, which in the case of Indian Point is a densely populated area.

[66] The assumptions about the radiation released are referred to as "source terms."

of the year 2000, more than 10 nuclear plant sites had more than 100,000 people living within a 10-mile radius.

The United States has one of the world's most well-developed regulatory systems for protecting nuclear power plants against sabotage and attack, and continues to upgrade its standards. Nonetheless, nuclear plant security requirements have not risen to the level needed to defend against credible threats comparable to the 9/11 attacks.[67]

Several problems stand in the way of addressing the risks of reactor sabotage and attack. The NRC gives less consideration to attacks and deliberate acts of sabotage than it does to accidents; the methodology for determining credible threats to nuclear facilities is flawed; and the process for determining whether reactor operators and the federal government can defend against such threats is inadequate.

The NRC Emphasizes Accidents More Than Sabotage

One underlying problem is that the risk of sabotage and terrorist attack has never fit comfortably into the NRC's regulatory framework, which focuses on preventing accidents. The NRC bases its approach to security on the presumption that—like catastrophic accidents—terrorist attacks are low-probability events. And the NRC maintains that a catastrophic accident is very unlikely to occur because multiple safety systems would have to fail simultaneously, and that the probability of that happening is very low. However, this logic fails when one considers deliberate damage.

Saboteurs may be capable of disabling multiple safety systems simultaneously, quickly leading to a meltdown and large release of radiation—a sequence of events that would be highly improbable if left to chance. In fact, severe releases resulting from the simultaneous failure of multiple safety systems are precisely what terrorists are seeking, to maximize the impact of their attack. Moreover, the engineering sophistication of the 9/11 attack on the World Trade Center suggests that terrorists are fully capable of using the wealth of publicly available information on the vulnerabilities of current and proposed nuclear plants to develop attack plans. *Thus the least likely accident sequences may well be the most likely sabotage sequences.*

The NRC's assumption that a terrorist attack is a low-probability event has meant that it has paid far less attention than justified to deliberate sabotage. For example, the NRC requires each nuclear plant to develop emergency plans to protect the public in the event of an accident, and conducts biennial exercises to determine whether plant owners working in conjunction with local, state, and federal entities can carry out their plans. However, the NRC does not yet require plant owners to develop emergency plans for sabotage or terrorist attacks, which could involve deliberate attempts to interfere with emergency evacuations (though it does plan to do so).

Even in the wake of the 9/11 attacks, the NRC has also universally dismissed terrorism from consideration in environmental impact studies, on the grounds that terrorist acts are too remote and speculative. These studies apply to licenses for expanding onsite spent fuel storage, 20-year extensions to operating licenses for nuclear plants, and site permitting for new reactors.[68]

The NRC also continues to disregard the risk of an attack on spent fuel pools at reactor sites. Spent fuel emits a large amount of heat as well as radiation. After the fuel is removed from a reactor, it is stored in adjacent pools of water for years. The water cools the fuel and shields personnel from radiation, and is replenished as needed. If the pool is drained for even a matter of hours, or the active cooling system is interrupted for a day or two, the zirconium cladding

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[67] Testimony submitted by Edwin S. Lyman, Union of Concerned Scientists, to the Subcommittee on Clean Air, Climate Change and Nuclear Safety, Senate Committee on Environment and Public Works (May 26, 2005).

[68] The NRC made several similar decisions on this point. For example, see the NRC's "Memorandum and order in the matter of Pacific Gas & Electric Company (Diablo Canyon Power Plant independent spent fuel storage installation), CLI-03-01 (January 23, 2003).

on the spent fuel rods could ignite spontaneously in air and the spent fuel could melt.

After about five years, the spent fuel is cool enough to be transferred to dry casks, which are cooled by a flow of air. However, U.S. reactor operators generally leave the spent fuel in the pools until they are full, and today they typically contain five times as much fuel as the reactors.

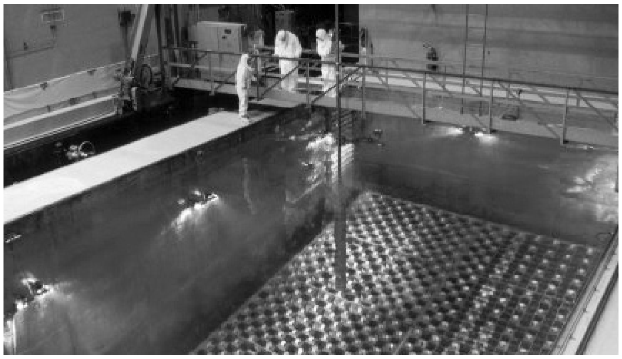
Unlike reactors, these pools are not protected by containment buildings. As a recent National Academy of Sciences study on the risks of spent fuel pools makes clear, a terrorist attack could, under some conditions, lead to the release of large quantities of radioactive material.[69] The report also concludes that the U.S. government does not fully understand the risks posed by a terrorist attack on a spent fuel pool. Another independent analysis found that a terrorist attack on such a pool could result in thousands of cancer deaths and hundreds of billions of dollars in economic damages.[70] These findings are consistent with those of a 1997 study by Brookhaven National Laboratory of the results of damage to irradiated fuel stored in pools.[71]

Recommendations:

The NRC should treat the risks of sabotage and attacks on par with the risks of nuclear accidents, and require all environmental reviews during licensing to consider such threats.

The NRC should require and test emergency plans for defending against severe acts of sabotage and terrorist attacks as well as accidents.

The NRC should require that spent fuel at reactor sites be moved from storage pools to dry casks when it has cooled enough to do so (within six years), and that the dry casks be protected by earthen or gravel ramparts to minimize their vulnerability to terrorist attack.



A nuclear power plant's spent fuel pool

Reactor Defenses Overlook Credible Threats

Under NRC regulations, plant owners must be able to defend against a "design basis threat" (DBT) with "high assurance." The DBT defines the size and capabilities of a group that might attack a nuclear facility. Publicly available NRC regulations omit the exact number of attackers and their specific weapons, as such details could aid potential attackers. (A confidential Adversary Characteristics Document specifies this information.)

Nevertheless, before 9/11, the DBT was widely known to entail three attackers, armed with nothing more sophisticated than handheld automatic rifles, and working with the help of a single "passive" insider whose role was limited to providing information about the facility and its defenses. A security program to protect against this threat would include controls on access to a facility, techniques for detecting an intrusion, and an armed response force.

In response to the 9/11 attacks, the NRC established a new DBT in April 2003, in close consultation with the nuclear industry.[72]

The April 2003 DBT entails a modestly larger attacking force that, according to press reports, is aided by an active but nonviolent insider, and has the communications ability to attack more than one target simultaneously. As *Time* noted:

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[69] National Research Council, Board on Radioactive Waste Management, *Safety and security of commercial nuclear fuel storage* (Washington, DC: National Academies Press, 2005), executive summary, p. 6.

[70] J. Beyea, E. Lyman, F. von Hippel, "Damages from a major release of ^{137}Cs into the atmosphere of the United States," *Science and Global Security* 12 (2004):125–136.

[71] R. J. Travis, R. E. Davis, E. J. Grove, and M. A. Azarm, Brookhaven National Laboratory, "A safety and regulatory assessment of generic BWR and PWR permanently shutdown nuclear power plants," NUREG/CR-6451 (August 1997).

[72] Letter from the NRC to owners of operating nuclear power plants, "Issuance of order requiring compliance with revised design basis threat for operating power reactors," EA-03-086 (April 29, 2003), online at *http://www.nrc.gov/reading-rm/doc-collections/enforcement/security/2003/ml030740002-dbt-04-29-03.pdf.*

Box 2. Attacks by Aircraft

The NRC's decision not to include aircraft attacks in the DBT is based partly on several studies conducted since 9/11 by the nuclear industry and the agency. These have basically considered two scenarios: (1) whether an aircraft hitting the reinforced concrete containment structure would penetrate the structure and damage the reactor vessel inside; and (2) whether an aircraft hitting the fuel-handling building would deposit enough burning jet fuel on top of the spent fuel pool to evaporate the water and uncover the irradiated fuel.

However, neither of these scenarios accurately reflects the real problems posed by aircraft attacks. An aircraft need not penetrate the containment structure to cause a meltdown. U.S. security regulations seek to prevent attackers from destroying a "target set" of equipment whose destruction would trigger a reactor meltdown. A single plant has many such target sets, some of which are entirely outside the containment structure. To cause a meltdown, an aircraft need only destroy one target set through impact and fire.

Nor does the vulnerability of the spent fuel pool stem largely from the possibility that water heated by burning fuel would slowly evaporate. All industry and NRC studies conducted before 9/11 concluded that a 707-sized aircraft crashing into a spent fuel pool would cause structural failure, allowing the water to quickly drain away. Although dire, that result was considered acceptable because the probability that a 707 would accidentally land on a spent fuel pool was very small. After 9/11, when it became clear that a deliberate attack was possible, the industry and the NRC changed that scenario to one that would require a less urgent response.

> *Before 9/11, the agency required plants to be able to thwart an attack by little more than an armed gang—three outsiders equipped with handheld automatic weapons and aided by a confederate working inside the plant. After 9/11, when al-Qaeda showed the ability to produce 19 operatives for a suicide mission on a single day, some security specialists anticipated a significant hike in the DBT. But the number of attackers in the revised DBT is less than double the old figure and a fraction of the size of the 9/11 group. (The NRC regards the exact number as an official secret.)*[73]

The 2003 DBT also assumes that the attackers have access to a wider range of weapons than did the pre-9/11 DBT. However, the new DBT does not include attacks by commercial airliners (see Box 2), smaller aircraft loaded with high explosives, or rocket-propelled grenades, a weapon widely used by insurgents around the world.[74, 75] Thus the new DBT is below the scale of the 9/11 threat, as some NRC officials have acknowledged.[76]

In investigating the decision making that led to the new DBT, the Government Accountability Office (GAO) found that important assumptions—such as the types of weapons available to attackers—were weaker than those first recommended by the NRC's threat assessment staff.[77] According to the GAO, the nuclear industry pressured the agency to remove attack characteristics it felt were too costly to defend against. The GAO also found that the NRC commissioners had based the DBT on a scenario a private security force could handle—without specifying any criteria for making that judgment. As the GAO noted, the

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[73] Mark Thompson, "Are these towers safe?" *Time*, June 20, 2005, pp. 34–48.

[74] U.S. Government Accountability Office, "Nuclear power plants: Efforts made to upgrade security, but the Nuclear Regulatory Commission's Design Basis Threat process should be improved," GAO-06-388 (March 2006).

[75] 72 FR 12705, *Federal Register* (March 19, 2007).

[76] Edwin Lyman, "Nuclear plant protection and the homeland security mandate," Proceedings of the Institute of Nuclear Materials Management 44th Annual Meeting, Phoenix, AZ, July 13–17, 2003, online at *http://www.ucsusa.org/global_security/nuclear_terrorism/nuclear-plant-protection-and.html*.

[77] U.S. Government Accountability Office, "Nuclear power plants: Efforts made to upgrade security, but the Nuclear Regulatory Commission's Design Basis Threat process should be improved," GAO-06-388 (March 2006).

lack of such criteria makes the commissioner's decisions opaque, and could result in a less-rigorous decision-making process.

Ideally, the DBT would reflect the plausible threats to nuclear facilities. However, that is not the NRC's current approach. Instead, as noted, the agency bases the DBT partly on the amount of money that industry is willing to pay for security. An agency that is independent of the nuclear industry is needed to ensure that nuclear plants are protected against *all* credible threats. This responsibility would logically fall to the Department of Homeland Security (DHS), which should be able to objectively analyze the threats to all critical elements of the country's infrastructure, including the nuclear power sector, and develop strategies to protect them. However, the DHS would first need to address the internal problems that have hampered its past performance.

Recommendation:

The Department of Homeland Security should set the DBT. It should assess the credible threats to nuclear facilities, determine the level of security needed to protect against those threats, and assign responsibility for countering each type of threat to either industry or the federal government. To conduct its independent assessments, the DHS would need full-time staff with the necessary expertise. It would also need to address the internal problems that have hampered its past performance.

The NRC would ensure that the nuclear industry complies with DHS requirements for protection against the DBT. The DHS should ensure that the government has enough resources to fulfill its responsibilities to protect nuclear facilities against credible threats beyond the DBT, as assigned by the DHS.

No Assurance of Adequate Defenses against Attack

The NRC periodically stages mock DBT-level attacks to determine if plant owners can defend against them (this is called force-on-force testing). At nearly half the nuclear plants tested before 9/11, three mock attackers were able to enter quickly and simulate the destruction of enough safety equipment to cause a meltdown—even though operators typically received six months' advance notice of which day the test would occur.[78]

The integrity of the tests themselves is also open to question. The NRC awarded Wackenhut the contract to supply the mock adversary team for all force-on-force tests, even though that company supplies the security officers for nearly half of all U.S. nuclear power plants. This situation represents a serious conflict of interest. In fact, the GAO found that one plant's security team performed better during a mock attack because it had obtained advance information about the planned attack scenario.[79]

Moreover, there is no mechanism to ensure that guards at nuclear power facilities have the skills they need. Although the NRC sets basic training and performance standards, reactor owners conduct their own training and certify their own security guards.

The federal government is responsible for defending against attacks of greater severity than the DBT. However, it has not shown an ability to do so. Indeed, the government has no mechanism for ensuring that it can provide such protection when needed.[80] For example, federal authorities do not conduct force-on-force tests to assess whether they can defend against such attacks. Instead, the government relies primarily on the intelligence community to provide advance warning of a pending attack.

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[78] Daniel Hirsch, David Lochbaum, and Edwin Lyman, "The NRC's dirty little secret," *Bulletin of the Atomic Scientists* 59, 03 (May/June 2003):44–51, online at *http://www.thebulletin.org/article.php?art_ofn=mj03hirsch.*

[79] U.S. Government Accountability Office, "Nuclear power plants: Efforts made to upgrade security, but the Nuclear Regulatory Commission's Design Basis Threat process should be improved," GAO-06-388 (March 2006), p. 8.

[80] Edwin Lyman, "Nuclear plant protection and the homeland security mandate" (2003), op cit.

Since 2004, the Department of Homeland Security has been evaluating the collective ability of local, state, and federal entities to prevent attacks on some nuclear plants, and to mitigate the results of attacks that do occur. However, such evaluations are not systematic, and the DHS does not have the authority or resources to ensure that private companies and local authorities accept and implement any recommendations that may emerge.

Recommendations:

The government should evaluate its ability to protect the public from attacks above the DBT level by periodically conducting tests that simulate an actual attack.

The Department of Homeland Security should serve as an independent evaluator of these tests—analogous to the role of the Federal Emergency Management Agency during biennial exercises of emergency plans for nuclear power plants—and have the authority and resources to ensure that its recommendations are followed.

The adversary force used in mock attacks on NRC-licensed facilities should be completely free of any conflicts of interest, and the appearance thereof.

The government should establish a federally administered program for licensing private nuclear security guards that would require them to successfully complete a federally run training course and undergo periodic recertification.

International Security Regulations

As with an accident at a nuclear plant, the consequences of a terrorist attack on a nuclear facility—radiological, economic, and political—would be felt well beyond national borders. However, no international mechanism exists to ensure that security measures at nuclear facilities are adequate.

In July 2005, the member states of the International Atomic Energy Agency voted to extend the scope of the Convention on the Physical Protection of Nuclear Material to cover security at domestic facilities (it previously covered only the security of nuclear materials transported between countries). However, the agreement includes only principles to which each country must commit. It does not set specific, mandatory standards for physically protecting nuclear materials, require peer review of national approaches to such protection, or include any enforcement mechanisms.

In fact, the amended convention will allow most signatories to continue to operate nuclear facilities with little or no change to their security protocols. For example, France does not require security personnel at nuclear power plants to carry weapons, and it will not have to change its policy. This international response to the enormity of the post-9/11 terrorist threat is insufficient.

Recommendation:

The United States should work to negotiate an international agreement that would establish stringent mandatory requirements for nuclear security, including verification and enforcement measures.

Chapter 4

Preventing Nuclear Proliferation and Nuclear Terrorism

Some of the technologies used for nuclear power are dual-use, meaning that they can also be used to produce the materials needed to make nuclear weapons—highly enriched uranium (HEU) and plutonium.[81] In particular, facilities for enriching uranium for use in power plant fuel can be used to make HEU, while facilities that reprocess spent reactor fuel produce plutonium. Nations that possess those technologies would find it easier to build nuclear weapons, and terrorists could acquire plutonium from reprocessing facilities. An expansion of nuclear energy could well increase these twin threats to U.S. and world security.

However, the expansion of nuclear power is just one factor of many that will affect the risks of nuclear proliferation and nuclear terrorism. For example, many states without nuclear weapons already have the technical capacity to produce material for them (usually based on experience with nuclear power). These nations could begin to produce nuclear weapons quickly should they make the political decision to do so. Barriers against civil power programs could slow—in some cases significantly—other states from pursuing a weapons program, buying time to remove political incentives for doing so. Nonetheless, the United States and the international community can do little to prevent a determined nation from eventually acquiring nuclear weapons.

In contrast, nuclear terrorism is preventable. Nuclear power programs are only one potential means for terrorists to gain nuclear weapons. Terrorists could steal a nuclear weapon, or buy one that had been stolen. Such actions can be prevented if nations that possess nuclear weapons guard them stringently, remove tactical nuclear weapons from deployment, and reduce their arsenals. Terrorist groups could also acquire HEU or plutonium and build a weapon themselves. Such groups are highly unlikely to acquire the means to produce these materials, because of the technical complexity, high cost, and scale of the necessary effort, so theft of material produced by others is the most probable route for terrorists to get the bomb. The United States and Russia possess large military stockpiles of HEU and plutonium outside of warheads. Providing stringent security for these materials, eliminating existing stocks, and eliminating the use of HEU for non-weapon purposes would go a long way toward preventing terrorists from acquiring nuclear weapons.[82]

Some countries produce plutonium—and, to a lesser extent, HEU—for use in civil reactors, and some have accumulated large stockpiles of

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[81] HEU consists of 20 percent or more of the isotope uranium-235.

[82] HEU can be eliminated by down-blending it to low-enriched uranium (LEU) for use as reactor fuel. LEU consists of less than 20 percent, but more than 0.7 percent, of the isotope uranium-235; reactor fuel for light-water reactors is usually enriched to 4–5 percent uranium-235. Thus HEU can be blended with depleted uranium—which is produced as a by-product of enrichment and contains less than 0.7 percent uranium-235—to produce LEU. Plutonium is best disposed of by mixing it with radioactive waste and vitrifying the mixture in a large solid log, which would be placed in a geologic repository.

In addition to prohibiting the use of HEU in reactors used to perform research and produce isotopes, this approach would also mean that nuclear-powered submarines would be fueled with LEU rather than HEU.

plutonium in facilities that are not well-guarded, leaving it vulnerable to theft.[83] The degree to which an expansion of nuclear power would increase the risk of nuclear terrorism depends largely on whether reprocessing—which produces plutonium—is part of the fuel cycle. *Reprocessing changes plutonium from a form in which it is highly radioactive and nearly impossible to steal to one in which it is not radioactive and could be stolen by an insider, or by force during routine transportation.*

The United States does not now reprocess its spent fuel, but the Bush administration is actively pursuing a program to do so (see Box 3).

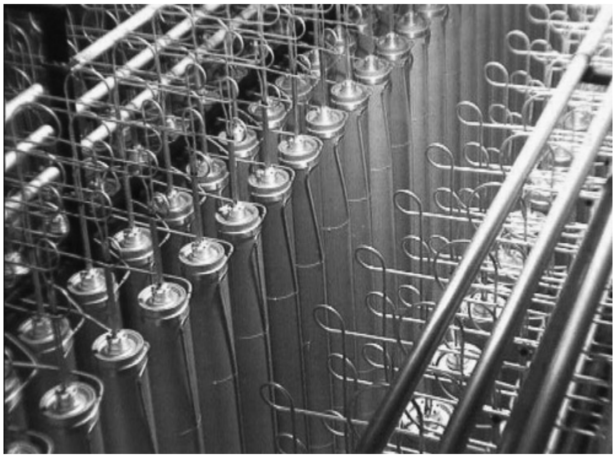
The Links between Nuclear Power, Proliferation, and Terrorism

Understanding the relationship between nuclear power, nuclear proliferation, and nuclear terrorism requires understanding how highly enriched uranium and plutonium are produced, and for what purposes.

Natural uranium consists mostly of two different "isotopes"—atoms of the same element that differ in the number of neutrons, and thus have slightly different weights. Natural uranium contains about 0.7 percent uranium-235, the isotope essential for nuclear weapons, 99.3 percent uranium-238, and trace amounts of uranium-234. To convert natural uranium into a form that can be used in both nuclear power and nuclear weapons, it must be "enriched" to increase the concentration of uranium-235.[84] Enriching uranium is both technically difficult and expensive, as it requires separating isotopes that have very similar chemical and physical properties. The enrichment process is thus the main barrier to producing uranium suitable for nuclear weapons.

Most of the world's power reactors, and all those in the United States, use low-enriched uranium (LEU) as fuel, which is typically enriched to between 3 and 5 percent uranium-235. While there are numerous ways to enrich uranium, state-of-the-art facilities now use cascades of "gas centrifuges," which are rapidly spinning cylinders. The centrifuges contain uranium in the form of gaseous uranium hexafluoride (UF_6), and the rapid rotation causes the slightly heavier uranium-238 atoms to move toward the outside wall of the cylinder. By removing the outer layer of UF_6 gas and leaving only the inner layer, which now has a slightly higher enrichment than the original gas, and repeating the process in a series of centrifuges, fuel makers can eventually enrich the uranium to the desired level.

Commercial facilities used to make LEU for power reactors can be reconfigured to produce HEU, which can be used for weapons. This can be done by reconnecting the centrifuges in a different pattern, or by substituting LEU for natural uranium in the feed. In fact, once uranium has been enriched to 4–5 percent uranium-235, roughly two-thirds of the work required to produce HEU (enriched to 93 percent) has been completed.



Gas centrifuges used to enrich uranium

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[83] Other isotopes—including uranium-233, neptunium-237, americium-241, and curium-244—can be used to make nuclear weapons, but they typically occur in much lower amounts than plutonium in the nuclear fuel cycles in common use, and thus pose less of a proliferation concern today.

[84] LEU contains greater than 0.7 percent and less than 20 percent uranium-235, while HEU contains 20 percent or more. LEU is not directly usable for weapons. HEU produced for weapons ("weapon-grade" uranium) is typically enriched to 90 percent uranium-235 or greater. HEU at all enrichment levels can be used to make nuclear weapons, but bomb makers would need larger quantities of HEU with lower enrichment levels. For example, the amount of material needed to make a fission weapon using a bare metallic sphere of HEU is roughly 60 kilograms for 90 percent-enriched HEU, 150 kilograms for 50 percent-enriched HEU, and 750 kilograms for 20 percent HEU.

Uranium-233, which is produced by bombarding naturally occurring thorium-232 with neutrons in a reactor, can also be used to make nuclear weapons. A mixture of U-233 and U-238 enriched to 12 percent or greater with U-233 is weapons-usable. If the mixture consists of U-233, U-235, and U-238, it is weapons-usable if [(weight of U-233 + 0.6 weight of U-235)/weight of total uranium] ≥ 0.12. See C.W. Forsberg, C.M. Hopper, J.L. Richter, H.C. Vantine, "Definition of weapons-usable uranium-233," ORNL/TM-13517 (Oak Ridge, TN: Oak Ridge National Laboratory, March 1998), online at *http://www.ornl.gov/sci/criticality_shielding/HopperPubs/DefWeaponsUsableU-233ORNLTM13517.pdf.*

Box 3. The Ups and Downs of U.S. Reprocessing Policy

The United States began reprocessing spent fuel from U.S. power reactors in the 1960s. This effort was reassessed after India's 1974 test of a nuclear weapon that used plutonium produced with reprocessing equipment it had imported under claims of "peaceful use." Under Presidents Ford and Carter, the United States adopted a no-reprocessing policy, arguing that the spread of commercial reprocessing facilities could spur the proliferation of nuclear weapons. They hoped the U.S. policy would help convince other countries to adopt a similar stance.

Several other countries, including Brazil, Pakistan, South Korea, and Taiwan, sought to follow India's example by launching "civilian" reprocessing programs. In each case, however, the effort was halted largely because of U.S. opposition. The United States questioned the nations' motive for acquiring these technologies, and argued that its own example showed that a robust nuclear power program does not require reprocessing.

In 1981 President Reagan reversed U.S. policy, but the U.S. nuclear industry continued to reject reprocessing because it made nuclear power more expensive. In 1993 President Clinton reversed the policy once again, stating that, "the United States does not encourage the civil use of plutonium and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes."[85]

In 2001, the Bush administration's National Energy Policy called for a major expansion of nuclear power, and for reconsidering reprocessing and the use of plutonium for fuel. In January 2006, the administration launched the Global Nuclear Energy Partnership (GNEP), which would entail reprocessing U.S. spent fuel and expanding the reprocessing capacity of "partner" nations. This would allow the United States and its partners to lease reactor fuel to other nations and require them to return the spent fuel for reprocessing, with the goal of dissuading them from acquiring their own enrichment and reprocessing facilities. (See Chapter 6 for more on this program.)

Today U.S. R&D is focusing on reprocessing technologies billed as more "proliferation-resistant" than conventional reprocessing. However, there is no convincing evidence that new designs will address the inherent proliferation problems of reprocessing (see Chapter 6). Only the "once-through" cycle—in which spent nuclear fuel is stored and eventually disposed of in a geologic repository—is proliferation-resistant enough to warrant consideration in the next 50 years.

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[85] William J. Clinton, Presidential Decision Directive (PDD)-13, "Nonproliferation and Export Control Policy," September 1993.

HOW POWER REACTORS PRODUCE PLUTONIUM

Plutonium exists naturally only in trace amounts. However, power reactors produce it automatically, when the uranium-238 in reactor fuel absorbs neutrons.[86]

Under normal use, reactors run for many months, to extract the most energy from the uranium. However, countries making plutonium for weapons usually operate reactors for a matter of weeks, to maximize the production of plutonium-239—the isotope most useful for nuclear weapons—and minimize the amount of other isotopes, such as plutonium-240.

The plutonium in spent power reactor fuel is roughly 24 percent plutonium-240. Such plutonium is known as "reactor-grade" (weapons-grade plutonium contains less than 7 percent plutonium-240). Still, nearly all isotopic mixtures of plutonium—including reactor-grade plutonium—can be used for nuclear weapons.[87]

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[86] Plutonium-239 is produced after uranium-238 absorbs one neutron, and higher isotopes of plutonium are produced when Pu-239 absorbs additional neutrons.

[87] Plutonium-238 is not usable by itself in nuclear weapons. It also has a relatively rapid decay rate and produces a relatively large amount of decay heat, which can accelerate degradation of high explosives used in nuclear weapons. Some analysts have therefore suggested that the presence of Pu-238 is a great challenge to the use of reactor-grade plutonium by terrorists, and that nuclear fuel cycles that increase the amount of Pu-238 in the plutonium they produce can enhance proliferation resistance. However, weapons designers maintain that the solutions exist to all the technical challenges posed by non-optimal plutonium mixtures or other isotopes potentially usable in nuclear weapons, such as neptunium-237, americium-241, and curium-244. See Bruce Goodwin, Lawrence Livermore National Laboratory, as quoted in Edwin Lyman, "The limits of technical fixes," in *Nuclear power and the spread of nuclear weapons: Can we have one without the other?* P. Leventhal et al., eds. (Dulles, VA: Brassey's, 2002), p. 167.

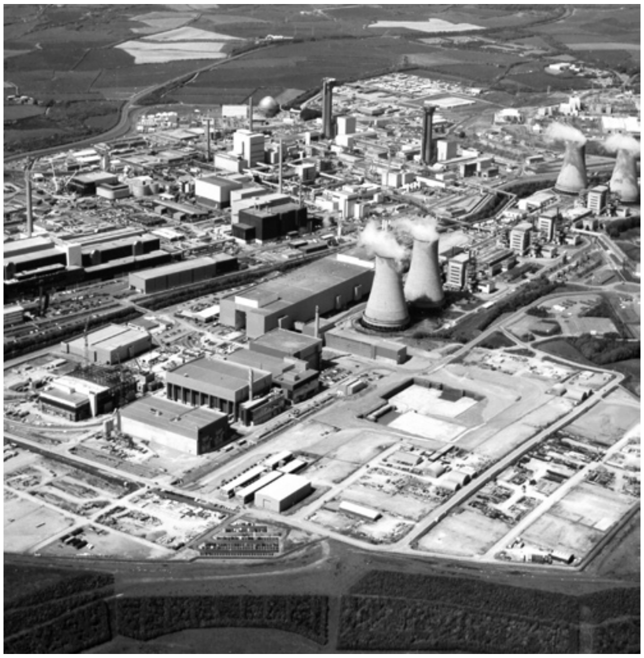
Although the relatively large amounts of plutonium-240 in reactor-grade plutonium can cause a weapon to detonate early and "fizzle," even a weapon that fizzles would cause an explosion equal to 1,000 tons (1 kiloton) of TNT or more.[88] According to a classified U.S. assessment:[89]

> [A] *subnational group using designs and technologies no more sophisticated than those used in first-generation nuclear weapons could build a nuclear weapon from reactor-grade plutonium that would have an assured, reliable yield of one or a few kilotons (and a probable yield significantly higher than that).*

A weapon of this size could kill tens of thousands of people if detonated in a city. Reactor-grade plutonium in the hands of terrorists is therefore a potent danger. Moreover, some nations have designed weapons that compensate for the "fizzle" problem. As the nuclear bomb-making expertise of terrorists grows, their ability to use reactor-grade plutonium will only increase.

Besides using plutonium in nuclear weapons, some countries use it as fuel for light-water reactors—in the form of a mixture of plutonium and uranium oxides known as MOX, for "mixed oxide." Another use for plutonium is in "breeder" reactors, which in theory can produce as much or more fissile material than they consume. Breeder reactors must be fueled with plutonium or HEU. However, most countries have abandoned work on such reactors because they are much more expensive and less reliable than light-water reactors.

To produce plutonium for use in nuclear weapons or nuclear fuel, it must be separated from spent reactor fuel in a "reprocessing" facility. Besides plutonium and the remaining uranium, spent fuel consists of highly radioactive elements that result from fission (termed "fission products"), and transuranic elements (neptunium, americium, and curium), which are produced when uranium atoms absorb neutrons.



The Sellafield reprocessing plant in England

Separating plutonium from spent reactor fuel is easier than enriching uranium because it involves separating different elements, rather than different isotopes of the same element. However, because the spent fuel is highly radioactive, this process requires heavily shielded facilities with remote-handling equipment.

The only reprocessing method used commercially today is PUREX (plutonium-uranium recovery by extraction). In this process, plutonium and the remaining uranium are separated from other elements in the spent fuel, and then from each other. The remaining highly radioactive waste is then stored—either in bulk tanks with active cooling systems, or melted with glass (vitrified) and cast into stainless steel canisters—before its final disposal. (Chapter 6 discusses other reprocessing processes proposed for commercial use in the United States.)

As noted, reprocessing changes plutonium from a form in which it is highly radioactive and nearly impossible to steal to one in which it is not

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[88] J. Carson Mark, "Explosive properties of reactor-grade plutonium," *Science & Global Security* 4,1 (1993).

[89] U.S. Department of Energy, "Nonproliferation and arms control assessment of weapons-usable fissile material storage and excess plutonium disposition alternatives," DOE/NN-0007 (1997), pp. 38–39, as quoted in Jungmin Kang and Frank von Hippel, "Limited proliferation-resistance benefits from recycling unseparated transuranics and lanthanides from light-water reactor spent fuel," *Science & Global Security* 13, 1–2 (2005):173.

radioactive and could be stolen by an insider, or by force during routine transportation. Expanding the number of facilities that reprocess spent fuel would provide terrorists with more potential sources of plutonium, and perhaps with easier access than at existing facilities. Thus, the degree to which expanded nuclear power would increase the risk of nuclear terrorism depends largely on whether reprocessing is part of the nuclear fuel cycle—internationally or in the United States.

The Inherent Shortcomings of IAEA Safeguards

The cornerstone of international efforts to prevent the further proliferation of nuclear weapons is the 1970 Nuclear Non-Proliferation Treaty (NPT), which prohibits all but five signatories (Britain, China, France, Russia, and the United States) from acquiring nuclear weapons, while facilitating the access of non-nuclear weapons states to nuclear technologies for peaceful uses. Because some nuclear technology such as reprocessing is dual-use, there is some tension between these two goals.

The NPT requires signatories without nuclear weapons to accept "safeguards" on certain materials and facilities that could be used as part of a weapons program. These safeguards are not designed to *prevent* misuse; nor are they capable of doing so. Instead, safeguards are designed to (1) detect actions that may indicate that a nation has a nuclear weapons program, giving the international community some advance warning and time to respond, and (2) deter such actions by threat of detection. The International Atomic Energy Agency (IAEA) monitors compliance with these safeguards.

However, the NPT does not address two major problems: latent proliferation, in which a nation's nuclear power facilities give it the capability to quickly make nuclear weapons, and the lack of timely detection of theft or diversion of materials for weapons. While the IAEA safeguards budget has long been inadequate, simply providing more-funding will not solve these problems, as they are due to the fundamental dual-use nature of nuclear technology.

THE CHALLENGE OF LATENT PROLIFERATION

Acquiring nuclear power technology may allow a nation that is in full compliance with the NPT to shorten the lead time to acquiring nuclear weapons while not revealing its intentions to the international community. North Korea's nuclear weapons program is a perfect illustration of this problem. When it was still party to the NPT, North Korea built a reactor and small-scale reprocessing facility—nominally for civil purposes. In 1992, IAEA inspectors discovered that North Korea had not been forthright about its reprocessing record, and suspected the country of having a nuclear weapons program. In March 1993, North Korea gave the required 90-day notice of its intent to withdraw from the NPT. The plutonium available to the country for building nuclear weapons—estimated to be some 35–45 kilograms, enough for six to eight nuclear weapons—comes from these facilities.[90]

The case of Iran, which is now developing the ability to enrich uranium, has also highlighted this problem. While Iran asserts that its enrichment facility will provide fuel for a small number of domestic nuclear reactors and for export, suspicions persist that Iran is actually seeking nuclear weapons. The fear is that Iran intends to use the facility to produce HEU for weapons, or to illicitly transfer centrifuge technology and equipment to clandestine facilities. Detecting clandestine centrifuge enrichment plants is difficult because they are compact, do not use large amounts of electricity, and do not produce easily observable signs that they are operating, such as radiation, heat, or chemical emissions (unless there is an accidental release of uranium hexafluoride gas).

To address this problem of latent proliferation, President Bush has proposed that some countries be denied access to dual-use fuel cycle technologies, such as enrichment and reprocessing, even if they are NPT members in good standing. In

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[90] Robert S. Norris and Hans M. Kristensen, "North Korea's nuclear program, 2005" *Bulletin of the Atomic Scientists* 61, 3 (May/June 2005):64–67.

exchange, those nations would have guaranteed access to foreign supplies of nuclear reactor fuel.

However, this proposal, made in response to the Iranian situation and other challenges to the NPT regime, is problematic for three reasons. First, it directly contravenes the NPT requirement that signatories have access to peaceful nuclear technologies, including enrichment and reprocessing technologies. Second, nations with nuclear weapons ambitions are unlikely to accept a prohibition on producing nuclear fuels. And third, the proposal would widen the gulf between nuclear "haves" and "have-nots" already embedded in the NPT, further undermining an already wobbly regime. After all, a non-nuclear weapons state could well persuade itself that it should share in the presumably profitable business of supplying enrichment services, or a least keep the jobs and the funds required to enrich uranium in the domestic economy, rather than depending on foreign suppliers. In any event, President Bush's proposal received little international support.

Indeed, the drive by some policy makers in the United States and elsewhere to expand the use of nuclear power plants by more countries—which would also require more enrichment facilities—would exacerbate the tension between fuel-cycle haves and have-nots.

LACK OF TIMELY DETECTION

Current safeguards are also inadequate to detect the diversion or covert theft of nuclear weapons materials in a timely manner. This is the case for commercial-scale facilities used to reprocess spent fuel and fabricate MOX fuel, which annually handle between several tons and many tens of tons of separated plutonium in solution or powder form. (Such facilities are referred to as bulk-handling facilities, as they handle materials in bulk rather than discrete, easily countable items.) Accounting for the plutonium moving through such facilities to within tens or even hundreds of kilograms is virtually impossible, allowing theft or diversion of this amount to go undetected for many years. Because a relatively simple implosion nuclear weapon can be made with roughly six kilograms of plutonium, any uncertainty in accounting for the annual amount of plutonium a facility processes is significant.

Several striking examples of this problem have come to light over the last decade. For example, in 1994 Japan revealed that during five years of operation, the total amount of plutonium unaccounted for at its Plutonium Fuel Production Facility in Tokai-mura had grown to 70 kilograms—enough for some 10 nuclear weapons. Japan insisted the missing material was "holdup"—dust that accumulates on equipment inside a facility. However, this could not be verified until the plant was shut down and "flushed out," which did not occur until 1996.

Similar problems occurred at the reprocessing plant in Tokai-mura, which started operating in 1977. Japanese officials acknowledged in January 2003 that accounting for a more than 200-kilogram shortfall in plutonium at the plant had required a 15-year investigation.[91] This amount was about 3 percent of the total plutonium separated by the plant during its 25 years of operation.

In 2005, a large leak of dissolved spent fuel at the Thorp reprocessing plant in the United Kingdom went undetected for more than eight months. The leaked solution contained some 19 metric tons of uranium and 190 kilograms of plutonium.[92] The fact that a shortfall in the amount of plutonium produced at the plant—enough for some 30 nuclear bombs—did not arouse concern for many months suggests that the theft of a significant amount could also go undetected.

Nuclear Terrorism

As noted, today's nonproliferation regime does not adequately address the acquisition of a nuclear weapon by a subnational group. Terrorists could try

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[91] Associated Press, "Missing plutonium probe latest flap for Japan's beleaguered nuclear power industry," Tokyo, January 28, 2003. Online at WISE-Paris news, *http://www.wise-paris.org/english/othersnews/year_2003/othersnews030128b.html.*

[92] British Nuclear Fuel Ltd. (BNFL), Board of Inquiry Report, "Fractured pipe with loss of primary containment in the THORP feed clarification cell," May 26, 2005, p.5.

to acquire a nuclear warhead from an existing arsenal or build one themselves. For terrorists seeking to build a nuclear weapon, the largest barrier is acquiring the fissile material needed to make one—either plutonium or HEU.

Under normal operations, commercial facilities for enriching uranium and fabricating uranium fuel do not handle HEU. Thus, while enrichment facilities present proliferation risks, their impact on the risk of nuclear terrorism is relatively small.

The same cannot be said of facilities that reprocess spent fuel and make MOX. Because they handle material that is directly usable for weapons, such facilities greatly increase the potential for nuclear terrorism. Separated plutonium at civilian facilities should be protected to the same degree as nuclear weapons. However, doing so would be costly, because conducting complete inventories would require frequent shutdowns.

The NRC does not require nuclear power facilities to protect nuclear weapons material as carefully as the DOE requires weapons facilities to do, as documented in a recent GAO report. The NRC and DOE also lack a common design-basis threat, largely because the NRC takes into account the threats against which a private force can reasonably be expected to defend. The GAO recommended that the level of protection be the same for materials that can be used to build nuclear weapons regardless of their location, but the two agencies rejected that recommendation. They did agree with the recommendation that NRC licensees be given the same legal authority as DOE sites to acquire heavier weaponry and use deadly force to protect weapons-usable material, as authorized by the Energy Policy Act of 2005.[93]

As noted, some countries use separated plutonium in MOX as fuel for light-water reactors (in what is termed a "closed" fuel cycle). While it is unlikely that MOX can be used directly to make nuclear weapons, the plutonium can be separated from the uranium in a straightforward chemical process. Moreover, MOX does not contain the highly radioactive components that make spent fuel difficult and dangerous to handle and reprocess. Thus the manufacture, transportation, and storage of MOX presents almost as great a terrorist risk as plutonium itself. The IAEA therefore regards MOX as "direct-use" material, and inspects it as often as it does pure plutonium. However, the United States and several other countries do not consider MOX as big a threat as separated plutonium, and do not protect it as vigorously.

In a "once-through" fuel cycle, in contrast, spent fuel is left intact and simply stored once it is removed from the reactor, for ultimate disposal in a permanent repository. In this case the plutonium remains imbedded in the highly radioactive spent fuel. Spent fuel contains cesium-137, which emits deadly gamma rays that can penetrate the human body. Someone standing one meter away from a typical spent fuel assembly that has been out of the reactor for a few years could receive a lethal dose in a matter of minutes. Because cesium-137 has a half-life of 30 years, this high dose rate persists for decades.[94]

Plutonium in spent fuel is therefore considered "self-protecting" for many decades after discharge.[95] Even terrorists willing to die for their cause would have little time to handle such highly radioactive material before becoming acutely ill.

The size and weight of a spent fuel assembly from a light-water reactor—typically 15 feet long and 700 kilograms (1,500 pounds) in weight—also make it difficult to steal. Accounting for the number of fuel assemblies is also straightforward. (Accounting for the spent fuel from heavy-water reactors such as CANDUs, which are used in Canada and a few other countries, is somewhat more difficult, because they are refueled while the reactor is operating.)

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[93] U.S. General Accounting Office (GAO), "Nuclear security: DOE and NRC have different security requirements for protecting weapons-grade material from terrorist attacks," letter to Rep. Christopher Shays (R-CT), Subcommittee on National Security and Foreign Affairs, Committee on Oversight and Government Reform, U.S. House of Representatives, September 11, 2007.

[94] The half-life of an isotope is the time it takes for half of the initial amount to decay. Because it is the decay process that produces radiation, an isotope with a short half-life is highly radioactive, but only for a short period of time. Isotopes with long half-lives emit only low levels of radiation, but do so over long periods of time.

[95] According to the IAEA, a material is self-protecting if its radiation dose rate exceeds 1 Sv/hr at one meter.

The bottom line is that a closed nuclear fuel cycle entails handling, processing, and transporting large amounts of material that is usable in nuclear bombs and often readily accessible and concealable. This gives terrorists numerous opportunities to acquire material for building a nuclear weapon. And during much of this process, the material cannot be accounted for precisely enough to ensure that an amount needed for one or more nuclear weapons has not been stolen.

Moreover, once plutonium is separated from spent fuel, it can be handled with little risk as long as care is taken to not breathe in any particles, because it does not emit body-penetrating gamma rays. Plutonium-oxide particles can become imbedded in the lining of the lungs, where very small quantities can cause cancer many years later. However, it would be difficult to inhale enough plutonium dust to cause prompt symptoms.

Commercial reprocessing programs have also produced a glut of separated and vulnerable plutonium. Global stockpiles of separated civil plutonium totalled roughly 250 metric tons as of the end of 2005—enough for 40,000 nuclear weapons.

The risk that terrorists will acquire separated plutonium is compounded by the lack of a verified international standard for protecting nuclear facilities, as Chapter 3 notes.

Recommendations:

The United States should reinstate a ban on reprocessing U.S. spent fuel, and actively discourage other nations from pursuing reprocessing. The security risks associated with current and near-term reprocessing technologies are too great.

The United States should take the lead in forging an indefinite global moratorium on operating existing reprocessing plants and building or starting up new ones. Reprocessing is not necessary for any current nuclear energy program, and the security risks associated with running reprocessing plants and stockpiling plutonium are unacceptable in today's threat environment, and are likely to remain so for the foreseeable future. A U.S. moratorium will facilitate a global moratorium.

The administration should pursue a regime—overseen by the International Atomic Energy Agency—to place all uranium enrichment facilities under international control, and to safeguard such facilities. To make the regime attractive to nations without those facilities, it would need to be non-discriminatory, and thus cover all existing enrichment plants.

The administration should work to complete a comprehensive Fissile Material Cutoff Treaty that prohibits the production of plutonium for any purpose—military or civil—and that institutionalizes and verifies the reprocessing moratorium. The treaty should also strengthen the growing consensus that HEU should not be used in civil applications by banning its use as fuel for power reactors.

Chapter 5

Ensuring the Safe Disposal of Nuclear Waste

Because the spent fuel removed from a nuclear reactor is highly radioactive, it must be disposed of in a way that protects the environment from contamination and living organisms from exposure. Radioactive isotopes can be spread by air or water, and can also become part of the food chain. While the radioactivity of spent fuel drops with time, according to a 1995 National Academy of Sciences study, the "peak risks [from a repository] might occur tens to hundreds of thousands of years or even farther into the future."[96] Isolating spent fuel from the environment is therefore a highly demanding task—for comparison, human civilization has existed for only some 10,000 years.

Several potential ways of handling spent fuel in the long term have been proposed—none of which are ideal. These include burying the waste below the seabed, launching it into outer space, and storing it on remote islands. However, the international scientific consensus is that spent fuel and other high-level waste should be stored underground in a "geologic" repository, where the geological properties of the surrounding area would provide the long-term stability needed to isolate the waste from the environment. The waste would sit inside tunnels drilled deep into the earth.

UCS concurs with this consensus, and believes that such a repository—if properly sited and constructed—can protect the public and the environment for tens of thousands of years. However, the choice of a repository location must be based on a high degree of scientific and technical consensus. When spent fuel is isolated in a geologic repository, the hazard to the public results from the slow corrosion of spent fuel and leakage of radionuclides into the environment—primarily through groundwater. The risk profile of a repository depends strongly on the geochemistry of the site, and changes with time as the result of radioactive decay.

Sweden, Switzerland, and the United States have decided to build such repositories, but none have begun to do so. Only the United States has chosen a potential site—at Yucca Mountain in Nevada. However, this facility faces several political and technical hurdles before it can be licensed. For example, although the site is unique among those proposed worldwide because it sits above the water table, leaks from the repository could still contaminate groundwater. In fact, analysts have found that rainwater travels much more rapidly through the layers of the proposed repository than originally believed, and thus that any leaked waste would also reach the groundwater more quickly.

Fortunately, there is no immediate need to open a permanent repository, as interim storage of spent fuel in dry casks at reactor sites is an economically viable and secure option for at least 50 years—if such sites are hardened against attack. New reactors could build in more robust interim storage from the beginning. However, the federal government must improve the security of these

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[96] National Academy of Sciences, *Technical bases for Yucca Mountain standards* (Washington, DC: National Academy Press, 1995).

onsite storage facilities, while also actively working to find a suitable permanent site.

Because 31 countries have power reactors and spent fuel, and about half of those have five or fewer reactors, it may ultimately be more practical to build several international repositories than for each nation to build its own repository. However, no country has seriously proposed hosting an international spent fuel repository.

U.S. Waste Disposal Framework

The Nuclear Waste Policy Act of 1982 established a legal framework for siting, constructing, and operating geologic repositories for high-level radioactive waste and spent nuclear fuel. The act directed the U.S. Department of Energy (DOE) to find at least five candidate sites across the country, and to recommend three to the president, who would choose one. The act also required the use of a similar process to select a second repository, so no single community would bear the entire burden of hosting all high-level waste.

According to the act, the first repository can accept up to 70,000 tons of high-level waste until the second repository begins operating. U.S. nuclear power plants have already produced 55,000 tons of spent fuel, and the 70,000-ton limit will soon be exceeded by the 104 reactors operating today.

The act stipulated that the NRC would license the repositories using standards set by the Environmental Protection Agency (EPA). The EPA initially required the repository to isolate the waste for at least 10,000 years. However, the 1992 Energy Policy Act nullified this standard, and directed the EPA to follow recommendations by the National Academy of Sciences. As noted, the 1995 NAS report found that the greatest risk to the public could occur long after 10,000 years: from tens to hundreds of thousands of years or even farther into the future."[97]

The 1982 act established the Nuclear Waste Fund to pay for the federal repository program. The law required that operators of nuclear power plants pay 0.1 cent per kilowatt-hour of electricity they generate, and that the federal government begin to accept spent fuel for disposal beginning in 1998. If reactor operators could not store all their spent fuel onsite before it was removed for disposal, the government would have to provide one or more interim storage facilities on government property.[98]

Yucca Mountain

In accordance with the Nuclear Waste Policy Act, the DOE identified eight potential repository sites. However, after several states with such sites objected, Congress amended the act in 1987, directing the DOE to assess only the Yucca Mountain site in Nevada.

In December 2001, the Government Accounting Office (GAO) found that some 300 technical issues regarding this site remained unresolved.[99] In January 2002, the U.S. Nuclear Waste Technical Review Board concluded that the scientific and technical basis for the DOE's assessment of Yucca Mountain was "weak to moderate."[100] Nevertheless, the secretary of energy recommended the site to the president, Congress supported the recommendation, and in July 2002 the DOE received authorization to apply to the NRC for a license to operate the site. The DOE plans to submit its application by June 2008, and to begin accepting spent fuel in 2017.[101]

However, the EPA was expected at press time to revise its standards for Yucca Mountain to require the government to show that it can protect the public for 1 million years after it closes the site. The DOE may be unable to meet such a standard, given limits in the ability of computer models to project what will occur at the site so far into the future.

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[97] Ibid.

[98] The maximum capacity of these facilities was set at 1,900 metric tons.

[99] U.S. General Accounting Office (GAO), "Technical, schedule, and cost uncertainties of the Yucca Mountain repository project," GAO-02-191 (December 2001).

[100] U.S. Nuclear Waste Technical Review Board, "2002 report to the U.S. Congress and the secretary of energy" (April 2003), online at *http://www.nwtrb.gov/reports/2002report.pdf.*

[101] According to DOE, an opening date of 2017 is a "best-achievable schedule." See *http://www.ocrwm.doe.gov/ym_repository/license/index.shtml.*

Recommendation:

Because licensing a permanent geologic repository for high-level waste may take a decade or more, especially if Yucca Mountain is found unsuitable, the Department of Energy should identify and begin to characterize other potential sites.

Interim Storage of Waste

Because a permanent repository is not yet available, the DOE has authorized many power plant owners to increase the amount of spent fuel in their storage pools by as many as five times the amount allowed by their original license. (Owners have filed nearly 60 lawsuits against the DOE seeking monetary damages for the costs of this storage, many of which have been settled, resulting in multimillion-dollar awards.)

As Chapter 4 notes, no containment buildings protect these pools, and an accident or terrorist attack that allows the water in a densely packed pool to rapidly drain away could cause the zirconium cladding on the fuel rods to catch fire and the spent fuel to melt, resulting in a significant release of highly radioactive isotopes such as cesium-137 (see Box 4, p. 48). Adding more spent fuel to these pools only compounds this potential problem, and increases the amount of radioactive material that could be released into the environment.

Plant owners whose storage pools are full have placed excess spent fuel in dry casks—typically steel cylinders welded or bolted closed to prevent leaks. These cylinders are placed inside a larger vault—typically made of concrete, which provides shielding from the radiation—and stored outdoors on concrete pads.

Dry casks used to store spent fuel

Although the dry casks would present less of a hazard than spent fuel pools if attacked, they remain vulnerable to weapons such as rocket-propelled grenades. These weapons could penetrate most dry casks and their vaults, igniting a zirconium fire and resulting in the release of significant amounts of radioactive material.

The security of these pools and dry storage sites is clearly unacceptable. However, interim storage of spent fuel in hardened dry casks can be made an acceptably safe and economically viable option for at least 50 years with a few relatively simple modifications, such as surrounding them with an earthen berm.[102]

Centralized Interim Storage

Given the delays and uncertainties surrounding Yucca Mountain, the Nuclear Energy Institute—an industry group—and some individual electric utilities have supported the idea of building one or more centralized interim storage facilities. Before spent fuel could be transported to such a facility, it would be placed in dry casks like those now used at some reactor sites (it would remain in those casks in a permanent repository). However, despite receiving a license from the NRC, a commercial facility on the Skull Valley Goshute Indian Reservation in Utah has encountered significant political roadblocks, including disapprovals by the Interior Department, and may never open.

The motive for centralized interim storage is largely political: it would provide a place for utilities to send their spent fuel in the event that a geologic repository is further delayed, thus satisfying the DOE's legal obligations. Consolidating spent fuel at one or more sites could also cut security costs and hence improve security. However, transporting spent fuel to these sites would entail safety and security risks. And even if spent fuel were

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[102] National Academy of Sciences, *Safety and security of commercial spent nuclear fuel storage* (Washington, DC: National Academies Press, 2005), pp. 60–73.

placed in dry casks and removed to an interim storage facility as soon as it was cool enough, all reactor sites would continue to store some spent fuel in pools. Thus centralized interim facilities would simply add to the number of spent fuel storage sites, unless they accepted fuel now stored at the 20 or so U.S. reactors that have been shut down or decommissioned.

Recommendation:
The federal government should take possession of spent fuel at reactor sites and upgrade the security of onsite storage facilities.

Box 4. Radioactive Isotopes

Spent fuel contains large quantities of radioactive isotopes, which are unstable and decay into other elements (called "daughter" elements) by emitting alpha or beta particles, gamma radiation, and/or neutrons. The new "daughter" element may itself be radioactive, and undergo further decay.

All four types of emissions are destructive to living cells, and can cause chromosome damage and cancer. If exposed to very high levels of radiation over a short period of time, a person will develop acute radiation syndrome, and will die in a matter of days or weeks from severe damage to organ tissue.

Different radioisotopes decay at different rates, expressed in terms of a "half-life," which is the time it takes for half of a quantity of isotope to decay. (Half of the remaining material—a quarter of the original amount—will then decay in another half-life, leaving one quarter. After three half-lives, an eighth of the material will remain, and so on.) Half-lives can vary from fractions of a second to millions of years. The more "radioactive" an isotope, the faster it decays, and the shorter its half-life. Thus isotopes with short half-lives emit high levels of radiation but for a relatively short amount of time, while isotopes with long half-lives emit lower levels of radiation but remain radioactive for a long period of time.

After irradiation for roughly three years, spent fuel from light-water reactors typically consists of about 1 percent uranium-235, 93–94 percent uranium-238, 4–5 percent fission products, 1 percent plutonium isotopes, and 0.1 percent other transuranic elements.

Fission products are created when uranium and plutonium split apart, and usually emit high-energy beta particles and/or gamma radiation, which can penetrate skin. Protection requires heavy shielding.

In the first several hundred years after spent fuel is removed from a reactor, the fission products pose the greatest risks to humans and other organisms (provided the spent fuel remains intact). After a few years, the gamma radiation from cesium-137 (Cs-137)—which has a relatively short half-life of 30 years—poses the greatest risk, and gives rise to the "self-protection" of spent fuel described in Chapter 4.

Transuranic elements do not exist in nature and are produced when uranium and then higher elements successively absorb a neutron. Transuranic isotopes, and uranium isotopes, usually emit alpha particles, which are stopped by the outer few layers of human skin. However, these particles can be very hazardous if they are inhaled or ingested, as they tend to deposit large amounts of energy in a small region, causing multiple DNA lesions in a single cell.

The most common transuranics in spent fuel are neptunium, plutonium, and americium. These elements are members of the actinide group, which includes uranium as well. While the radioactivity of these actinides varies, some isotopes are very long-lived, and hence less radioactive. Neptunium-237 has a half-life of about 2 million years, while plutonium-239, -242, and -244 have half-lives of 24,000, 380,000, and 80 million years, respectively.

Reprocessing as a Waste Management Strategy

Some argue that reprocessing spent fuel will reduce the volume of high-level waste needing disposal in a geologic repository. Because spent fuel from light-water reactors is mainly uranium, these proponents of reprocessing maintain that removing it would result in a smaller quantity of waste.

However, it is the level of heat generated by the waste—not the volume—that determines how much waste a repository can store. If the waste is packed too densely in the tunnels, and the heat output is high enough that the temperature exceeds the boiling point of water, permanent changes could occur in the chemical, mechanical, and hydrological properties of the surrounding rock. Such changes could compromise the ability of the repository to isolate the waste from the environment over the required time period.

As Chapter 4 noted, some countries have used the PUREX method to reprocess spent fuel over the past several decades (or contracted with other countries to do so). This process separates both plutonium and uranium from spent reactor fuel, and then from each other. The transuranic elements plutonium, americium and curium are the main sources of heat in spent fuel after a few hundred years; americium and curium remain in the waste stream and would require disposal in a permanent repository. Thus, the PUREX process does not significantly reduce the heat output, or the size of the required repository.[103]

Countries that reprocess spent fuel stockpile the plutonium in interim storage facilities. Some of these countries, including Great Britain, have no plans for this material. Other countries have used some of the plutonium as MOX fuel in reactors, or plan to do so.

However, separating the plutonium for potential use does not eliminate its hazards—it greatly aggravates them, as the stockpiles are much more vulnerable to release from an accident or a terrorist attack than if they were immobilized in a stable matrix such as glass and placed in a permanent repository. Transporting, processing, and irradiating the plutonium also increase the risk that it will be released into the environment.

If the plutonium is used in MOX fuel, the spent MOX fuel contains more long-lived transuranics than spent uranium fuel. No country has reprocessed the plutonium in spent MOX fuel and then reused it, because the costs and safety risks rise with each reprocessing cycle. In fact, although France has a policy of reusing the plutonium in spent MOX fuel, it has not done so, and ultimately may not (see Box 5, p. 50). Thus, spent MOX fuel must also be placed in a permanent geologic repository, further diminishing the benefits of the repository.

Moreover, while spent fuel consists mostly of uranium with roughly the same composition as natural uranium, separated uranium is contaminated with other uranium isotopes that are more radioactive, and with trace quantities of transuranic isotopes. This contaminated uranium can cause difficulties for enrichment plants and reactors. Thus France and other countries that reprocess spent fuel have not used the separated uranium as new fuel, but have instead stockpiled it. This uranium is not high-level waste, but it is difficult to classify in the U.S. system, so the method for disposing of it is uncertain. It would most likely require disposal in a geologic repository similar to the Waste Isolation Pilot Plant (WIPP) in New Mexico. (WIPP itself can accept only transuranic waste from military activities, and could not accept such uranium—see Box 6, p. 52)

Wastes from Reprocessing

As noted, reprocessing also generates additional waste streams. When spent fuel is chopped and

continued on page 52

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[103] If spent fuel is directly disposed of in the Yucca Mountain repository, the rock surrounding the fuel would reach its peak temperature in about 2,000 years. If the spent fuel was reprocessed, and the plutonium used to manufacture MOX fuel for existing reactors, much of it would fission, but the spent MOX fuel would also contain other transuranic isotopes that contribute more decay heat in the first few thousand years. Steve Fetter and Frank N. von Hippel, "Is reprocessing worth the risk?," *Arms Control Today*, September 2005, online at *http://www.armscontrol.org/act/2005_09/Fetter-VonHippel.asp.*

Box 5. Nuclear Power in France

Some proponents of expanding nuclear power in the United States point to the French nuclear program as worth emulating. France's 58 pressurized light-water reactors produce 75–80 percent of its electricity demand.[104] (The 104 U.S. reactors produce about 20 percent of U.S. electricity.)

Électricité de France—a government-owned entity—produces all the country's electricity. Government-owned companies have built all the French nuclear reactors, and Cogema, also government-owned, reprocesses the spent fuel.

Because the French government controls all aspects of the industry, it was able to significantly expand nuclear power after the 1973 oil crisis. As a high-level nuclear official recently cautioned, the French period of nuclear power expansion was specific to its time and place, and could not be extrapolated to other countries, or even duplicated in France today.[105]

Centralized control has also enabled the government to limit reactors in France to a few standardized designs. In contrast, the U.S. electricity sector is a patchwork of privately and publicly owned regional and national utilities, and U.S. reactors are of many different designs. Thus the French industry benefits from a shared learning curve, but also has a greater risk of "common-mode" problems than the U.S. industry.

An example is the impact of rising surface temperatures on nuclear power plants. During the heat waves of 2003 and 2006 in Europe, drought reduced the volume of some of the bodies of water used to cool reactors in France and other countries, raising the potential for excess heating of these bodies of water. As electricity demand peaked, Électricité de France sought waivers of the environmental restrictions, while countries such as Germany and Spain reduced power levels or shut down plants entirely. Even so, France ended up having to shut some plants and import electricity to meet demand.[106]

Thus excessive reliance on nuclear power increases the vulnerability to common-mode phenomena that could affect the performance of many or all nuclear plants.

Shortfalls in Economics and Safety

Although France has recently been forced to open its borders to the European electricity market, French nuclear power did not previously compete in the energy market, and thus did not have to respond to cost-cutting pressures. The French government provides little public information on the sector, making it difficult to compare the cost of electricity generated by nuclear power in France and the United States. The French government also releases far less information on safety practices or its safety record than the U.S. Nuclear Regulatory Commission. However, despite the lack of public information, the French experience reveals clear economic and safety downsides to an electricity grid that is highly dependent on nuclear energy.

For example, regional demand for electricity can fluctuate during the course of a day by 50 percent or more, depending on the seasons and the day of the week. In the United States, nuclear power plants usually continue to operate at their peak capacity to provide baseline electricity. Fluctuating demand is met by coal or natural gas plants, which can easily adjust their output, or "load-follow." (The NRC does not prohibit load-following by U.S. reactors, but it occurs only rarely.) Because fuel and operating costs are a relatively small component of the cost of the electricity reactors generate, operating them at full capacity is most economical.

However, because nuclear plants generate so much of its electricity, France must use some of its nuclear

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[104] Uranium Information Centre, "Nuclear power in France," Briefing Paper 28 (March 2007), online at *www.uic.com.au/nip28.htm.*

[105] Remarks by Olivier Caron, governor for France, to the IAEA Board of Governors, Carnegie Institute of International Peace, January 18, 2007.

[106] Susan Sachs, "Nuclear power's green promise dulled by rising temps," *Christian Science Monitor*, August 10, 2006. Because these restrictions are designed to limit the increase in the temperature of the water, a smaller volume of cooling water would lower the acceptable thermal emissions rate.

reactors to load-follow—either by lowering and raising reactor power levels, or by shutting down reactors during times of low demand, such as on weekends. Thus the average "capacity factor"—the amount of electricity reactors produce versus what they are capable of producing—is less than 80 percent in France, which is low by world standards. In the United States, the average capacity factor has been roughly 90 percent during the 2000s.

Using nuclear reactors to load-follow also raises safety risks. For example, when a reactor's power level is allowed to fluctuate, the potential for sudden power spikes rises. These spikes could produce significant fuel damage, which could lead to a fuel meltdown. Variations in power output also put cyclic stresses on fuel pellets, cladding, and structural materials in the reactor, which could lead to fatigue and other damage. And the risk of accidents does not fall when the reactor is shut down for short periods, as the decay heat of the fuel remains high. Thus during these periods there is risk but no benefit. Optimizing the electricity grid so nuclear plants do not have to load-follow is a more efficient and safer policy.

Stockpiles of Nuclear Waste and Plutonium

Like the United States, France has made little headway in developing a geologic repository for long-lived nuclear wastes. However, France's approach has created problems that the United States does not have. France ships spent reactor fuel to a complex in La Hague, Normandy, for storage and eventual reprocessing. However, the uranium from its reprocessed spent fuel is not being consumed, as it is more expensive to turn into reactor fuel than mined uranium, so thousands of tons have accumulated.

But perhaps the biggest failure of this program is its nearly 50-ton stockpile of separated plutonium. France initially intended to use the plutonium in its fast-breeder reactor program. However, this program failed on performance and safety grounds (Phénix and Superphénix were plagued with liquid sodium leaks, and Phénix experienced unexplained reactivity increases).

Stuck with a growing stockpile of plutonium, France required Électricité de France to start using MOX fuel made from this plutonium in its light-water reactors—even though MOX is several times more expensive than low-enriched uranium, and its use required reactor modifications and restrictions on operations. So far France has licensed only 20 of its first-generation pressurized-water reactors to use MOX fuel. At today's rate of use of MOX, eliminating the 50-ton stockpile of separated plutonium will take decades.

Security measures for this stockpile are inadequate. France does not employ armed guards at nuclear power plants, even plants storing and using MOX fuel. And vehicles containing plutonium and MOX traveling on French roads are poorly guarded. After extensively videotaping the trucks used to transport plutonium oxide from La Hague to MOX fuel fabrication facilities in Cadarache and Marcoule, and recording their license plates, Greenpeace activists intercepted a truck carrying 150 kilograms of plutonium and chained themselves to it. Even though this incident occurred within meters of a French military base, off-site responders took two hours to arrive and arrest the activists.[107]

Meanwhile, France has blocked implementation of binding physical protection standards by the International Atomic Energy Agency, which could have compelled France to upgrade its security. If France were to adopt standards for protecting plutonium appropriate for the post-9/11 era, the already poor economics of its program for using plutonium would only worsen.

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[107] Greenpeace, "Greenpeace blocks top secret transport of plutonium in France, revealing global proliferation threat is not in Iraq," online at *http://www.greenpeace.org/international/press/releases/greenpeace-blocks-top-secret-t or http://tinyurl.com/3a2643.*

dissolved for reprocessing, volatile fission products—such as the noble gases and the halogens—are released as gases. These radioactive gases are either vented through smokestacks or trapped on filters. If released, the gases contribute to both near-term and long-term radiological exposure. If captured, the spent filters must be disposed of as radioactive waste. (Whether they are considered low-level or transuranic waste depends on the concentrations and types of radionuclides—see Box 6.)

Besides the high-level liquid waste from the first extraction cycle, reprocessing plants have also generated large volumes of liquid wastes. For example, liquids used to clean solvents and flush pipes become radioactive. After some radionuclides are removed, their volume can be reduced through evaporation; the water vapor is vented out the smokestack. The remaining concentrated waste will be low-level or transuranic waste, depending on its composition. But there is a trade-off between reducing or eliminating liquid waste and increasing the volume of solid low-level and transuranic wastes that require disposal beneath the earth's surface.

Reprocessing also generates large amounts of solid wastes ranging from the cladding removed from spent fuel to contaminated clothing. When a reprocessing plant is eventually deactivated and decommissioned, it also must be disposed of in a waste facility (the type of facility will again depend on the type and quantity of contamination).

Recommendation:

The United States should drop its plans to begin a reprocessing program.

Box 6. Three Types of Nuclear Waste

According to the 1982 Nuclear Waste Policy Act, "**high-level radioactive waste**" is either "the highly radioactive material resulting from the reprocessing of spent nuclear fuel," or other highly radioactive material that must be permanently isolated according to the NRC. For instance, the intensely radioactive liquid waste resulting from the reprocessing of uranium to produce plutonium for U.S. nuclear weapons falls into this category. Yucca Mountain is intended to store such waste.

The Department of Energy defines **transuranic waste** as radioactive waste containing more than 100 nanocuries of alpha-emitting transuranic isotopes per gram with half-lives of more than 20 years. The DOE requires that this waste be buried in a geologic repository. The Waste Isolation Pilot Plant in New Mexico is the only licensed repository for such waste.

The 1982 Nuclear Waste Policy Act defines "**low-level radioactive waste**" as all radioactive material that is not high-level radioactive waste, spent nuclear fuel, or transuranic waste. However, the NRC does not recognize "transuranic waste," considering it instead as a type of low-level waste known as "greater than Class C," which it judges "not generally acceptable for near-surface disposal." Thus commercial low-level waste facilities, which bury waste in shallow trenches, do not accept transuranic waste.

Chapter 6

Evaluating New Nuclear Reactor Designs

Some argue that new reactor designs on the drawing board will provide much greater levels of safety, security, and proliferation resistance than today's generation of reactors. It is true that new reactors *could* be designed to be safer than today's plants, and much more resistant to sabotage and attack. However, for designs in the early stages of development, enough information is not yet available to judge whether this potential will be realized.

Some of the claims about the benefits of new designs that are fairly well developed have merit, while some are exaggerations. While some design features would correct major deficiencies in today's plants, cuts in other safety margins, uncertainties in how these reactors would actually work in practice, and the need to develop advanced materials to perform under punishing conditions may well offset the safety benefits. And the opportunity to significantly increase the resistance of the next generation of reactors to sabotage is not being fully exploited.

Some new reactor designs would use fuels containing plutonium. Unless these fuels were intentionally contaminated with highly radioactive fission products, these reactors and the facilities needed to produce their fuel would give terrorists and nations more opportunities to acquire plutonium for use in nuclear weapons. That is, fuel cycles for these designs would be less proliferation-resistant than those of today's reactors, which use low-enriched uranium fuel.

Overview of Reactor Safety

Probabilistic risk assessments conducted by U.S. reactor owners find that today's nuclear power plants will have a core meltdown from an accidental malfunction during full-power operation every 20,000 years on average.[108] Because about 100 reactors now operate in the United States, a severe accident of this type is expected to occur every 200 years on average. That is, the probability that such an accident will occur is about 0.5 percent each year.

Of course, such estimates entail many uncertainties. And they do not take into account "external" events such as earthquakes and fires, or accidents occurring during shutdown. The probability of a core meltdown from external events is roughly comparable to that from a plant malfunction.[109] Thus, the overall probability of a meltdown could be roughly double the cited estimate. This suggests that we can expect a severe accident to occur within the existing fleet every 100 years on average.

If the United States were to significantly increase the number of reactors, vendors and owners would have to reduce the average probability of a meltdown to merely maintain today's level of risk. For example, if the number of U.S. reactors doubled or tripled, the probability of a meltdown would need to fall by 50–66 percent to break even. To *reduce* the risk of a meltdown in the larger fleet, the average probability would need to fall by a factor of more than two or three. However, the NRC's long-standing policy is *not* to require that

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[108] NRC, "Status of accident sequence precursor and SPAR model development programs," SECY-02-0041 (March 8, 2002), p. 10.

[109] Nuclear Energy Institute, "Severe accident mitigation alternatives (SAMA) analysis," Guidance Document, NEI 05-01 (Rev. A), November 2005, pp. 710.

new nuclear plant designs be demonstrably safer than today's fleet.

The safe operation of nuclear power plants depends on many factors, including the quality of plant management and NRC oversight. The safety systems embedded in a plant's design are also important. One approach is to use emergency cooling systems that limit the conditions that could occur in a design-basis accident to well below those that could cause significant fuel damage. For example, the NRC requires the temperature of the fuel cladding (the metal wrapper around the uranium fuel rods) in a loss-of-coolant accident to stay below 1,200°C; designing the emergency core-cooling system to keep the temperature below 1,000°C would provide a significant safety margin.

Another approach is to provide "defense-in-depth": redundant and diverse safety systems to prevent accidents and mitigate their impact should they occur. However, the NRC's Advanced Reactor Policy Statement falls short of requiring defense-in-depth. Instead, it expects advanced reactors to "provide more margin prior to exceeding safety limits and/or utilize simplified, inherent, passive or other innovative means to reliably accomplish their safety functions".[110]

In fact, NRC policy effectively discourages greater defense-in-depth by emphasizing efforts to prevent accidents as more "cost-beneficial" than efforts to limit their impact.[111] While preventing accidents is clearly preferable to dealing with their consequences, new designs are not mature enough to ensure that defense-in-depth can be downgraded safely.

Another key issue is the degree to which reactor systems have been thoroughly tested through operating experience. Features that look good on paper but have not been validated in practice should not receive the same weight in safety assessments as those with significant operating experience.

The Safety of Generation III+ Designs

U.S. utilities have shown a great deal of interest in the Westinghouse AP1000 and the General Electric Economic Simplified Boiling Water Reactor (ESBWR), which are known as Generation III+ designs (see Box 7). About half of the letters that the NRC has received from utilities stating their intent to apply for combined operating licenses reference one of these designs. These reactors incorporate simplified and "passive" approaches to reactor safety, such as relying on gravity rather than motor-driven pumps to provide a backup water supply in the event of a loss-of-coolant accident. However, because of greater uncertainties in how these approaches would actually work in practice, they may not actually be safer than existing designs.

These two reactors do fix some obvious safety problems inherent in today's reactors. For example, the AP1000 is far less vulnerable than existing reactors to a total loss of AC power—that is, when both off-site power is lost and on-site emergency generators fail to work. As a result, risk assessments by the designers find that the probability that these reactors will experience a severe accident is much lower. For example, these analyses show that the probability of a core meltdown is 100 times lower than that for today's plants.

However, little experience with full-scale reactors operating at full power is available to validate computer models of these safety systems, producing significant uncertainties.[112] In its analysis of the AP600 design—predecessor of the AP1000—the NRC assumed that uncertainties could raise the probability of a meltdown by a factor of 100. If that were also true for the AP1000, it would negate the cited 100-fold improvement in meltdown probability, leaving the AP1000 as vulnerable to meltdown as reactors in today's fleet. Reactor designs with passive safety systems could use active systems as backups, but the NRC asserts that such

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[110] NRC, "Regulation of Advanced Nuclear Power Plants: Statement of Policy," 51 FR 24643 (July 8, 1986).

[111] NRC Final Rule, "AP1000 design certification," SECY-05-0227, Enclosure 2 (Environmental Assessment) (December 14, 2005), p. 24.

[112] According to the NRC, uncertainties in the values of the driving forces "can be of comparable magnitude to the predicted values themselves." See *AP1000 final safety analysis report*, Chapter 19, "Severe accidents" (September 13, 2004), p. 10.

an approach would be inconsistent with the "design objective." It would also be more expensive.

The designers of these reactors have also weakened defense-in-depth—presumably to cut costs. For example, these two designs have less robust containment systems, less redundancy in safety systems, and fewer safety-grade structures, systems, and components.

A prime example of reduced defense-in-depth is the AP1000 containment structure. Designers of that reactor project an electricity cost about 25 percent lower than that of the AP600, because the AP1000 nearly doubles the power output of the AP600 without a proportionate increase in construction cost. However, many of the cost savings come from scaling back the size of the containment building. The ratio of containment volume to a reactor's thermal power is a good measure of its containment capacity, and the AP1000 has a ratio lower than that of most reactors now operating.[113]

In addition, unlike today's reactors, the AP600 and AP1000 require a cooling water system to protect the containment structure from rupturing after an accident. Because this creates another potential failure mode, it increases the risk that such a rupture would occur. Westinghouse considered using a more robust containment structure, but

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[113] For the AP1000, the ratio is 605 cu. ft./MWth, compared with 885 cu. ft./MWth for the AP600, which is in the range of that of most operating pressurized-water reactors. The AP1000 ratio is higher than that for ice-condenser PWRs, of which there are nine in the United States.

Box 7. Generation III and III+ Reactor Designs

Until recently, designers of new U.S. reactors have focused on evolutionary refinements that aim to make plants safer and less costly to build. The NRC has certified four evolutionary designs: the General Electric (GE) Advanced Boiling Water Reactor (ABWR) and the Westinghouse System-80+, AP600, and AP1000 pressurized-water reactors (PWRs).

The first three reactors are sometimes referred to as Generation III, and the AP1000 as Generation III+ (see Table 1, p. 58).[114] Although GE has sold ABWRs abroad, no U.S. company has ordered any of these reactors because of their high cost.[115]

The ABWR and System-80+ are very similar to existing plants, while the AP600 was designed to significantly reduce capital costs "by eliminating equipment which is subject to regulation."[116] This means, in part, that the plant was designed to reduce the number of safety-related systems, structures, and components (SSCs)—those needed to mitigate design-basis accidents.[117] Such equipment must meet a much higher standard than commercial off-the-shelf equipment, and may raise its cost by a factor of 10.[118]

To reduce the number of safety-related SSCs, the AP600 uses more dual-purpose systems, such as the one that provides water to steam generators during both normal operation and accidents. The AP600 also employs "passive" safety features (e.g., natural convection cooling, a reliance on gravity rather than motor-driven pumps). Because concrete and steel account for over 95 percent of the capital cost of today's reactors, Westinghouse made it a priority to reduce the size of safety-related SSCs such as the containment vessel.

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[114] The characterization of designs as Generation III or Generation III+ is based on chronology rather than design features. The DOE refers to the three designs that obtained NRC certification in the 1990s as Generation III, even though the AP600 is more closely related to the Generation III+ AP1000 (which received certification in 2006) than the other two Generation III designs.

[115] In March and June 2006, two Texas utilities, Amarillo Power and NRG Energy, announced that that they had filed letters of intent with the NRC to apply for licenses to build a total of four ABWRs. However, this is only a preliminary step, and does not commit the utilities to actually order the reactors.

[116] Westinghouse Electric Co., *http://www.ap600.westinghousenuclear.com/plant.htm.*

[117] NRC 10 CFR § 50.2, "Definitions."

[118] Westinghouse Electric Co., "Risk-informed assessment of regulatory and design requirements for future nuclear power plants," prepared for DOE Nuclear Energy Research Initiative, DOE/SF21902 (January 2003), p. 38.

Box 7. Generation III and III+ Reactor Designs (continued)

Westinghouse claims that this reactor reduces the probability of accidents because it has fewer active safety systems, which can be unreliable. To enhance the effectiveness of the AP600's passive safety features, Westinghouse limited the power rating of the reactor to 600 MWe. The net result is a higher projected cost for electricity from the reactor than from the ABWR and System-80+, even though the AP600 has a lower projected capital cost. As a result, the AP600 has not proved attractive to U.S. utilities.

In response, Westinghouse developed the AP1000—a scaled-up version of the AP600 with a power rating nearly twice as high (more than 1,100 MWe)—to reduce the projected cost of electricity through economies of scale. Several U.S. utilities have indicated interest in building this reactor.

Designs under NRC Review

As of October 2007, four other Generation III+ designs were in the NRC certification pipeline, although only one had formally begun the licensing process.[119] The others are under pre-application review, which the NRC typically uses to identify major safety and technical issues and determine what research would be needed to resolve them.[120]

The one design now under certification review is GE's 1,500 MWe Economic Simplified Boiling Water Reactor (ESBWR). Like the AP1000, it uses passive safety features and a higher power rating than U.S. plants operating today to reduce its capital cost per installed kilowatt.

The three reactor designs in pre-application review are the U.S. Advanced Pressurized-Water Reactor (APWR) developed by Mitsubishi; the Evolutionary Power Reactor (EPR) developed by the French company Areva; and the Pebble Bed Modular Reactor (PBMR) developed by the South African national electric utility Eskom.

The 1,700 MWe U.S. APWR is a large evolutionary variant of today's pressurized-water reactors. Like the ABWR, it offers some incremental improvements over its Generation III counterparts, but it does not have novel features.

In contrast, the EPR stands apart from other Generation III+ PWR designs. This design, a joint French-German project known in Europe as the European Power Reactor, has considerably greater safety margins than designs developed to meet only NRC standards, because it fulfills more stringent safety criteria developed jointly by France and Germany. For instance, the reactor has a double-walled containment structure, whereas the NRC requires only a single-walled one. The EPR also has systems intended to stabilize and contain the reactor core in the event that it overheats, melts, and breaches the reactor vessel. Areva plans to apply for NRC design certification in late 2007.

The PBMR is distinctly different from today's commercial light-water reactors. It uses helium gas as a coolant, a graphite moderator, and fuel consisting of very small uranium-oxide spheres coated with a corrosion-resistant material and embedded in tennis-ball-sized graphite "pebbles." These pebbles travel from the top to the bottom of the reactor vessel as the reactor operates. Each module has a low power rating (about 150 MWe), so a typical power station would require about a dozen PBMR modules. The PBMR represents another attempt to reduce capital costs through a design intended to be safer.

PBMR promoters bill the reactor as "inherently safe," arguing that the reactor's low power density and the high-temperature integrity of its fuel would prevent significant fuel damage, even in an accident in which the reactor

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[119] The NRC has initiated pre-application discussions of other reactor designs, but these were terminated by the prospective applicant. Several years ago Framatome ANP (now Areva NP) began pre-application discussions of its SWR-1000, but the company is no longer pursuing certification because there is no interest on the part of U.S. utilities. In 2002, Atomic Energy of Canada Ltd. (AECL) initiated a pre-application review of an advanced version of the heavy-water-moderated CANDU reactor, the ACR-700, but the review apparently became inactive after AECL's U.S. utility partner, Dominion Resources, decided to pursue the ESBWR instead.

[120] NRC, "Backgrounder: New nuclear plant designs" (August 2006).

lost all coolant. (If the fuel retains its integrity, there is no radioactive release.)

The U.S. utility Exelon submitted the PBMR design to the NRC for pre-application review in 2000, arguing that the reactor was so safe it did not require a pressure-resisting containment vessel—only a less costly "confinement" building. However, because the NRC did not have enough technical information, it had not been able to assess whether the proposed confinement building was acceptable when Exelon terminated the review in 2002.

In 2004, the Pebble Bed Modular Reactor Co. (PBMR Ltd.), a consortium that includes British Nuclear Fuels and Eskom, informed the NRC that it wanted to resume the pre-application review, and intends to apply for design certification in 2007.[121] In July 2006 Eskom submitted several white papers to the NRC as part of the pre-application review process.

Designs Not Yet under Review

In addition to the designs under active review, the NRC has had preliminary discussions with vendors and other interested parties about three other reactor designs.

The IRIS (International Reactor Innovative and Secure) design, a pressurized-water reactor with a relatively low power rating of 325 MWe, is being developed by an international consortium headed by Westinghouse.

Westinghouse submitted the IRIS design to the NRC for pre-application review, but that review became inactive when the company told the NRC that it did not intend to apply for design certification until 2010.

The second design is Toshiba's 4S (Super Safe, Small, and Simple) reactor, which could also be classified as a Generation IV design (see Box 8, p. 59). This liquid-sodium-cooled fast reactor would provide 10 MWe of power and have a core lifetime of 30 years. The reactor is intended for use in remote regions and is designed to operate without routine maintenance. To minimize the need for security personnel, the reactor would sit inside a sealed vault 30 meters underground.

Toshiba offered to provide a free 4S reactor to the town of Galena, Alaska, as a demonstration project if the company received a license from the NRC. Although the town voted in December 2004 to accept Toshiba's proposal, and officials from Galena and Toshiba met with the NRC in February 2005, Toshiba has not yet initiated an NRC pre-application review.

Fast reactors are typically fueled with either highly enriched uranium or plutonium. The limited number of public documents describing the Galena proposal are vague or inconsistent regarding the type of fuel that would be used, but the most recent documents indicate that the fuel would consist of 17–19 percent-enriched uranium.[122]

The third project is a 2006 proposal by General Atomics to build a test high-temperature gas-cooled reactor at the University of Texas–Permian Basin. General Atomics originally initiated a pre-application review of its full-scale Gas Turbine Modular Helium Reactor (GT-MHR) in 2001, but told the NRC in 2005 that it intended to terminate those discussions. Its proposal for a test reactor would require a less extensive approval process than that for a full-scale power reactor.

The large number of reactor designs potentially seeking certification—some well outside the experience base of most NRC staff—and uncertainties about which proposals are serious present significant challenges to the NRC. It is difficult for the agency to justify developing the expertise to evaluate unfamiliar reactor concepts when it is unclear whether they are viable.

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[121] British Nuclear Fuel's stake is now owned by Westinghouse.

[122] Toshiba, "4S reactor: First meeting with NRC pre-application review," Nuclear Regulatory Commission, Washington, DC, October 23, 2007, p. 18.

Table 1. New Reactor Designs

	Design Characteristics	Coolant	Moderator	Role of Reprocessing	NRC Status
Generation III					
Advanced Boiling Water Reactor (ABWR)	Very similar to current reactors; 1350 MWe	Water	Water	Not necessary	Certified August 1997
System-80+	Very similar to current reactors; 1350 MWe	Water	Water	Not necessary	Certified May 1997
AP600	Passive safety features, but weaker containment structure; 600 MWe	Water	Water	Not necessary	Certified December 1999
Generation III+					
AP1000	Passive safety features, but reduced containment strength and volume; approx. 1,100 MWe	Water	Water	Not necessary	Certified December 2005
Economic Simplified Boiling Water Reactor (ESBWR)	Passive safety features; approx. 1,550 MWe	Water	Water	Not necessary	Company applied for design certification August 2005; under review
Evolutionary Power Reactor (EPR)	Greater safety margins; double-walled containment structure; severe accident mitigation features; approx. 1,600 MWe	Water	Water	Not necessary	Under pre-application review; application expected in 2007–2008
Pebble Bed Modular Reactor (PBMR)	Claimed to be “inherently safe;” containment building is not pressure-resistant; 150 MWe per module	Helium gas	Graphite	Large spent fuel volumes may spur reprocessing	Under pre-application review; company intends to apply in 2007
U.S. Advanced Pressurized-Water Reactor (APWR)	1,700 MWe; similar to current PWRs	Water	Water	Not necessary	Under pre-application review
International Reactor Innovative and Secure (IRIS)	Relatively low power (325 MWe); innovative “integral” design	Water	Water	Not necessary	Company hopes to apply for design certification by 2010
Super Safe, Small and Simple (4S)	Liquid-sodium-cooled fast reactor; 10 MWe	Liquid sodium	None (no moderation required in fast reactor)	Not necessary if fuel is LEU as planned	Company has not begun pre-application review
Generation IV					
Very High Temperature Reactor (VHTR)	Designed for cogeneration of hydrogen; approx. 300 MWe	Helium gas	Graphite	Not necessary	Under development by the DOE; has not applied for design certification
Supercritical-Water-Cooled Reactor (SCWR)	Large plant; reference design of 1,700 MWe	Water	Water	Not necessary	Under development by the DOE; has not applied for design certification
Gas-cooled Fast Reactor (GFR)	Design size of 288 MWe	Helium gas	None	Required	Under development by the DOE; has not applied for design certification
Lead-cooled Fast Reactor (LFR)	Low-power reactors would have long periods between refueling; designs range from 50 to 1,200 MWe	Liquid lead or lead-bismuth	None	Required	Under development by the DOE; has not applied for design certification
Sodium-cooled Fast Reactor (SFR)	Designs range from 150 to 1,700 MWe	Liquid sodium	None	Required	The DOE will likely seek NRC licensing under GNEP, but has not applied for design certification

Source: NRC, “New nuclear plant designs,” Backgrounder (August 2006), online at *http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/new-nuc-plant-des-bg.pdf*; and U.S. Energy Information Administration, “New reactor designs,” online at *http://www.eia.doe.gov/cneaf/nuclear/page/analysis/nucenviss2.html.*

Note: The coolant removes the heat produced by the reactor core. The moderator slows down fast neutrons released by atoms undergoing fission in the reactor core.

rejected it as not cost-beneficial. Westinghouse also apparently considered adding a "core catcher"—a structure designed to cool a molten core after it breaks through the reactor vessel—to the AP1000. However, the company determined that this system, too, was not cost-beneficial, given that external cooling of the reactor vessel is supposed to prevent the core from melting through it.[123]

However, the French Commissariat à l'Énergie Atomique is reported to have independently studied whether the AP1000 would maintain vessel integrity in a core-melt accident and "did not arrive at a positive result."[124] Even if it were used, a core catcher is a novel feature with its own significant uncertainties,

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[123] NRC Final Rule, "AP1000 design certification," SECY-05-0227, Enclosure 2 (December 14, 2005), pp. 15–23.

[124] Ann MacLachlan, "IRSN's analyses prompted Areva to revise core-catcher design," *Inside NRC* (June 26, 2006), p. 8.

Box 8. Generation IV Reactor Designs

In addition to the Generation III and III+ designs of commercial reactor vendors, the Department of Energy is sponsoring R&D on advanced reactor systems at national laboratories and universities. This program—known as Generation IV—is nominally pursuing five systems. Two are thermal reactors: the Very High Temperature Reactor (VHTR) and the Supercritical-Water-Cooled Reactor (SCWR).[125] Three are fast reactors, which would use plutonium-based fuels: the Gas-cooled Fast Reactor (GFR), the Lead-cooled Fast Reactor (LFR), and the Sodium-cooled Fast Reactor (SFR).[126]

The goals of the Generation IV program are ambitious:

> *Generation IV . . . systems will provide sustainable energy generation . . . will minimize and manage their nuclear waste . . . will have a clear life-cycle cost advantage . . . will have a level of financial risk comparable to other energy projects . . . will excel in safety and reliability . . . will have a very low likelihood and degree of core damage . . . will eliminate the need for offsite emergency response . . . will increase the assurance that they are . . . the least desirable route for diversion or theft of weapons-usable materials and provide increased physical protection against acts of terrorism.*[127]

Although begun in the late 1990s, the Generation IV effort was given new life with the endorsement in the Bush administration's 2001 National Energy Policy of "reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant." The program received a significant increase in funding and a related program, the Advanced Fuel Cycle Initiative (AFCI), was initiated. The AFCI is intended to develop the "reprocessing and fuel treatment technologies" called for in the National Energy Policy and the Global Nuclear Energy Partnership (GNEP).

The DOE has selected a specific class of reprocessing technologies, known as UREX+, and a specific advanced reactor—the sodium-cooled fast reactor—for pursuit under GNEP. Thus it was unlikely at press time that the DOE under the Bush administration would continue to fund significant R&D efforts for other AFCI and Generation IV technologies, although it could maintain these efforts at a small level. (The Very High-Temperature Reactor, the only design with the potential to produce hydrogen fuel for transportation, will proceed under a separate initiative.)

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[125] Thermal reactors use a material known as a moderator to slow down fission neutrons to energies at which they can most efficiently fission uranium-235 and plutonium-239.

[126] Fast reactors do not employ a moderator, and use fast neutrons for fission. In 2005, the DOE said it would not be emphasizing the SFR because it is "already at a fairly advanced state of development," but would be "monitoring the progress of the SFR internationally." DOE, Office of Nuclear Energy, Science and Technology, "Generation IV nuclear energy systems ten-year program plan, fiscal year 2005," vol. I (March 2005), p. vi.

[127] U.S. Nuclear Energy Research Advisory Committee (NERAC), "A technology roadmap for Generation IV nuclear energy systems" (September 23, 2003), p. 7, online at *http://nuclear.gov/nerac/FinalRoadmapforNERACReview.pdf.*

and may not have much better than a 50 percent chance of working.[128] If the probability of a core meltdown is not reduced, the AP1000 may actually be *less* safe than current plants, because its containment is less robust.

Other safety margins are also lower for the AP1000 than the AP600. According to the NRC, "The AP1000 design is less tolerant of equipment failures than the AP600." During a significant loss-of-coolant accident, the AP1000 requires that two "accumulators"—which inject additional cooling water at a high rate—work as planned, whereas the AP600 requires only one.[129] The higher power density of the AP1000 core compared with the AP600 also significantly reduces the margin between the operating temperature of the fuel cladding and the maximum limit of 2,200°F, in the event that a large pipe break or other system failure produces a loss of cooling water.

As noted, Westinghouse used a standard cost-benefit analysis to evaluate the merits of adding features designed to reduce the risk of severe accidents. The NRC criticized Westinghouse's methods:[130]

> *The applicant's estimates of risk do not account for uncertainties either in the CDF* [calculated risk of a core meltdown] *or in the offsite radiation exposures resulting from a core damage event. The uncertainties . . . are fairly large because key safety features of the AP1000 are unique and their reliability has been evaluated through analysis and testing programs rather than through operating experience.*

Nevertheless, the NRC certified the AP1000 design, on the grounds that the certification process for the AP600—whose risk analysis did include uncertainties—found that none of these safety improvements would be cost-beneficial. However, because the AP1000 has lower safety margins than the AP600, a measure that was not cost-beneficial for the AP600 could well be for the AP1000. For instance, passive cooling of the reactor vessel would likely be more effective for the AP600 because of its lower power density, so it would have less need for a core catcher. Thus, an analysis showing that a core catcher would not be cost-effective for the AP600 would not necessarily apply to the AP1000.

Questions about the safety of the ESBWR are similar to those for the AP1000.

THE EVOLUTIONARY POWER REACTOR

In contrast to the AP1000 and the ESBWR, the Evolutionary Power Reactor (EPR) developed by the French company Areva has features that may make it safer than today's U.S. reactors. The EPR has four independent safety trains, each of which is a complete set of safety systems designed to mitigate an accident, including backup power supplies.

The French and German governments have also required Areva to enable the reactor's safety systems and spent fuel building to withstand the crash of a military aircraft. And in the event of an accident or sabotage, the EPR's double-walled containment structure would hold up better than the standard single-walled one. The EPR is also designed with a core catcher to prevent the core from melting through the reactor vessel during a severe accident. (As noted, the core catcher is a novel feature, and may not have much better than a 50 percent chance of working.) However, the design for the EPR at Olkiluoto, Finland, had to be upgraded to comply with a post-9/11 requirement that the plant be able to withstand the impact of a commercial aircraft.[131] Without a similar NRC requirement, the U.S. EPR could, and most likely would, be based on the initial, less robust design.

The question remains, however, as to whether the manufacturer will strip down the EPR to meet less rigorous NRC standards to better compete in the U.S. market. Areva has said that the EPR is a "global product" that will retain the full set

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[128] Ann MacLachlan, "IRSN's analyses prompted Areva to revise core-catcher design," *Inside NRC* (June 26, 2006), p. 8.

[129] NRC Final Rule, "AP1000 design certification," SECY-05-0227, Enclosure 2 (Environmental Assessment) (December 14, 2005), p. 17.

[130] Ibid, p. 23.

[131] Areva NP, "Finnish EPR Olkiluoto 3," brochure, 2006, p. 14, online at *http://www.areva-np.com/common/liblocal/docs/press/OL3_EPR_press%20kit__06_06_en.pdf.*

of design features wherever it is built, including the United States.[132] But unless the NRC imposes stricter standards for new reactors, the EPR and other designs with greater safety margins will be at an economic disadvantage.

THE PBMR: INHERENTLY SAFE?

The Pebble Bed Modular Reactor (PBMR) is distinctly different from today's commercial light-water reactors. It uses helium gas as a coolant, a graphite moderator, and fuel consisting of very small uranium-oxide spheres coated with a corrosion-resistant material and embedded in tennis-ball-sized graphite "pebbles." These pebbles travel from the top to the bottom of the reactor vessel as the reactor operates.

The PBMR has been promoted as a "meltdown-proof" reactor that would be free of the safety concerns typical of today's plants.[133] However, while the PBMR does have some attractive safety features, several serious issues remain unresolved. Until they are, it is not possible to support claims that the PBMR design would be significantly safer overall than light-water reactors. And gaining a better understanding of these issues will likely take time.

The most significant unresolved issue involves how the PBMR's fuel would hold up during an accident, which is the key to the reactor's safety. The coating of PBMR fuel can maintain its integrity to temperatures of about 1,600°C—several hundred degrees higher than the temperature at which conventional reactor fuel would begin to degrade in a loss-of-coolant accident.[134] The claim that the reactor is meltdown-proof rests on the assertion that fuel temperatures would not exceed 1,600°C, even if the reactor loses coolant. (When reactor fuel degrades, it releases highly radioactive fission products.)

However, computer models are used to predict peak fuel temperatures during an accident. Modeling the movement of the fuel pebbles in the reactor—and hence accurately predicting the peak temperature—has proven extremely difficult. This is significant; as the fuel temperature exceeds 1,600°C, the ability of the fuel to retain fission products rapidly diminishes.[135] Thus the safety case for the PBMR depends largely on an ability that does not yet exist—namely, to accurately predict peak fuel temperatures during accidents.

Because designers maintain that fuel performance will prevent a meltdown, the PBMR does not have a containment vessel. However, the reactor does need a containment structure to ensure safety, given the uncertainty concerning the fuel performance.

A second unresolved safety issue concerns the reactor's graphite coolant and fuel pebbles. When exposed to air, graphite burns at a temperature of 400°C, and the reaction can become self-sustaining at 550°C—well below the typical operating temperature of the PBMR. Graphite also burns in the presence of water. Thus extraordinary measures would be needed to prevent air and water from entering the core. Yet according to one expert, "air ingress cannot be eliminated by design."[136]

THE IRIS

The IRIS (International Reactor Innovative and Secure), a design with a relatively low power rating of 325 MWe, is being developed by an international consortium headed by Westinghouse. IRIS differs from conventional reactor designs in that the pressure vessel would contain all the primary components, such as coolant pumps and steam generators, along with the reactor core.

Because of its passive safety features, the IRIS incorporates only a "pressure-suppression" containment—a thin spherical steel shell—instead of a large steel-reinforced concrete structure as in conventional reactors. Based on their claim that the IRIS design is inherently safe because of its

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[132] Areva NP, "Design features unique to the U.S. EPR," Technical Report (Rev. 0) (November 2006), p. ii.

[133] Stewart Brand, "Environmental heresies," *Technology Review*, May 2005.

[134] Conventional fuel for light-water reactors is zirconium-clad uranium oxide.

[135] Edwin Lyman, "The Pebble-Bed Modular Reactor: Safety issues," *Physics and Society Newsletter*, October 2001.

[136] Andrew Kadak, professor of the practice, Nuclear Engineering Department, MIT, "Safety issues for high-temperature gas-cooled reactors," online at *http://web.mit.edu/pebble-bed/Presentation/HTGRSafety.pdf*.

passive safety features, its designers also plan to seek an exemption from the NRC's off-site emergency planning requirements. Eliminating the containment structure and emergency planning will likely decrease the overall safety of the design.

THE 4S REACTOR

The 4S (Super Safe, Small, and Simple) reactor may be small and simple, but there is no reason to believe it is "super safe." This 10 MWe reactor is designed to operate without routine maintenance, as the core would have a lifetime of 30 years, and is intended for use in remote regions. To minimize the need for security personnel, the reactor would sit inside a sealed vault 30 meters underground.

However, the inability to conduct routine maintenance creates the potential for severe problems. A former NRC regional administrator framed this issue well: "If we look at the problems at existing plants, the most expensive problems have been the ones that no one ever imagined would have to be fixed."[137]

Another problem is that the coolant for the 4S reactor is sodium, which is highly reactive and burns if exposed to water or air. In the event of an accident, it could produce a more powerful explosion than is likely with today's reactors. Toshiba's proposal to supply a 4S reactor to Galena, Alaska—an isolated community with no industrial infrastructure—highlights the danger of such schemes. If an unexpected problem were to develop, the community would have no resources on hand to deal with it.

The Safety of Generation IV Designs

In addition to the Generation III+ designs of commercial reactor vendors, the DOE is sponsoring R&D on advanced reactor systems at national laboratories and universities (see Box 8, p. 59). Two are thermal reactors and three are fast reactors that would use plutonium-based fuels. One goal of these designs—known as Generation IV—is greater safety. However, there is no basis for assuming that any of the five designs now under study would be significantly safer than today's nuclear power plants.

First, Generation IV designs have little or no operating experience, so detailed computer models would be needed to accurately predict their vulnerability to catastrophic accidents. However, this project is still in its infancy, so developing and extensively validating computer models for each design will be a formidable task.

Second, all the designs use coolants that are highly corrosive under normal operating conditions, and will therefore require advanced structural materials that can perform well in extreme environments. This is true even for the Very High Temperature Reactor (VHTR), which uses inert helium gas as a coolant, as low levels of impurities in the coolant would be highly corrosive at the operating temperature of 1,000°C.[138] Development of these advanced materials is speculative, and failure to meet the performance goals would translate into lower safety margins and higher operating costs.

Third, to reduce costs, Generation IV designs aim to reduce safety margins wherever possible. This is at odds with the fundamental concept of defense-in-depth, in which backup safety systems compensate for uncertainties in the performance of the main safety systems.

For example, one Generation IV goal is to eliminate the need for off-site emergency response plans, which are a critical component of defense-in-depth strategy. The confidence to take such an unprecedented step can come only from a wealth of operating experience, which is lacking for the new designs. And any new design will have to undergo the "break-in" phase of the aging curve, according to which higher failure rates are expected at the beginning and end of a plant's lifetime. Accidents at U.S. reactors have conformed to this curve.[139]

Fourth, the Sodium-cooled Fast Reactor (SFR) and Lead-cooled Fast Reactor (LFR) have inherent

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[137] Ellis Merschoff, NRC, in "New energy technologies: A policy framework for micro-nuclear technology," Rice University, August 2001, p. 5.

[138] See, for example, C. Cabet, A. Monnier, and A. Terlain, "Corrosion of high-temperature alloys in the coolant helium of a gas-cooled reactor," *Materials Science Forum* 461–464 (2004):1165–1172.

[139] Eric Young, "The risk of a lifetime," *Catalyst* (the magazine of UCS) 3, 2 (fall 2004).

safety problems because of their coolants. Lead-bismuth coolant is less reactive and has a higher boiling point than sodium coolant. However, it is extremely corrosive, and when irradiated produces highly volatile radioisotopes (polonium-210 in particular) that would be a challenge to contain even under normal operating conditions.

As noted, the use of liquid sodium as a coolant presents serious safety challenges. According to a 2002 Department of Energy report,[140]

> *It is also true that sodium as a reactor coolant has two major drawbacks: its chemical reactivity, and its positive void coefficient of reactivity in most plutonium-fueled applications. . . . There have been small sodium leaks (and small fires) at essentially every sodium-cooled reactor plant built; in some cases, several of them. These incidents, though, do not disqualify the coolant from further use.*

The "void coefficient of reactivity" indicates how the reactor's power output would change if steam bubbles (or voids) form in the coolant. Power increases if the coefficient is positive. Thus, if the core overheats and the liquid metal coolant boils, the reactor's reactivity and power will rise rapidly. This intrinsic positive feedback can lead to a rapid increase in power and disrupt the core, while reducing the amount of time operators have to take mitigating action.

The NRC requires that reactors have a prompt negative feedback response to any increase in reactivity.[141] Therefore, the NRC could not license an SFR with a positive sodium void coefficient under today's guidelines.

Nonetheless, the NRC could make an exception. NRC staff concluded in the 1990s that "a positive void coefficient should not necessarily disqualify a reactor design," provided the risk to the public remained low.[142] Scientists at Argonne National Laboratory often argue that the EBR-II—an experimental SFR in Idaho that operated from 1961 to 1994—was a "passively safe" reactor that shut itself down after a safety test, despite its positive void coefficient. However, the shutdown relied on expansion of the reactor's metal fuel elements as they heated, which is not "prompt inherent nuclear feedback," and cannot be relied on to compensate for increases in reactivity.

Design changes can reduce or eliminate the positive void coefficient in fast reactors. For instance, the 4S is designed to maintain a negative void coefficient over its entire operating cycle. However, such changes usually increase the amount of reactivity in control systems, and therefore raise the severity of other types of reactivity accidents.[143] Whether there is an optimal design for fast reactors that can make their overall risk acceptable is far from clear.

Perhaps even more serious than the positive void coefficient is that, unlike most light-water reactors, fast reactors are not in their most reactive configuration under normal operating conditions. This means that an event that causes the core to become more compact—such as a core meltdown—could substantially raise reactivity, resulting in a rapid power increase that could vaporize the fuel and blow the core apart.[144] Such an explosion—dubbed a "hypothetical core disruptive accident"—would be similar to the explosion of a very small nuclear fission weapon, with a yield comparable to that produced by a ton of TNT.

These problems are already severe for SFRs that use only mixtures of plutonium and uranium. However, the DOE ultimately plans to adapt its advanced recycling reactor to use fuels that also contain the highly radioactive actinides neptunium, americium, and curium (see p. 69), which

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[140] Nuclear Energy Research Advisory Committee and Generation IV international forum, "Generation IV roadmap: Description of candidate liquid-metal-cooled reactor systems report," GIF-017-00, December 2002, p. 34.

[141] The NRC's General Design Criterion 11 states that, "the reactor core and associated coolant systems shall be designed so that in the power operating range the net effect of the prompt inherent nuclear feedback characteristics tends to compensate for a rapid increase in reactivity." 10 CFR Part 50, Appendix A.

[142] NRC, "Issues pertaining to the advanced reactor (PRISM, MHTGR and PIUS) and CANDU 3 designs and their relationship to current regulatory requirements," SECY-93-092, p. 23.

[143] Ibid.

[144] E.E. Lewis, *Nuclear power reactor safety* (New York: Wiley, 1977), pp. 245–261.

tend to increase the severity of these reactivity problems. Designing cores for such reactors that can both effectively fission these actinides and be acceptably safe will be a major challenge.

Some new reactor designs represent the next evolutionary step for nuclear power, incorporating features intended to make the plants safer and more economical. These features, however, are largely untested in the field or have very limited operating experience. Other new reactor designs have operated only in cyberspace and have never experienced the trials and tribulations of real-world operation. The gremlins hiding in their designs have not yet been exposed, let alone exorcised.

Recommendation:

The NRC should require that all new reactor designs be safer than existing reactors. Otherwise designs with greater safety margins will lose out in the marketplace to designs that cut costs by reducing safety.

New Reactor Designs and the Threat of Sabotage and Attack

No matter how safe a reactor design with regard to accidents, it remains vulnerable to sabotage by adversaries with some knowledge of its weaknesses and the ability to exploit them. Thus the NRC now withholds much information about reactor vulnerabilities from the public. Given information now available, only one new reactor design—the EPR—could be significantly more secure against attack and sabotage than today's reactors, but this will only be the case if the NRC requires that new reactors be able to withstand the impact of a commercial aircraft.

Efforts to protect reactors against sabotage and attack will always rely largely on external measures: guns, guards, and gates. However, certain design principles could reduce the vulnerability of the reactor core to sabotage. For example, the larger the "target set" of subsystems that must be destroyed to cause core damage—and the more widely separated these targets—the more sabotage-resistant the design. The goal is to avoid designs—such as those of some plants now operating—where one properly placed explosive could disable an entire target set and cause core damage.

The NRC long ago developed principles for reducing reactors' vulnerability to sabotage, such as completely separating redundant sets of safety equipment, and hardening heat-removal systems against attack.[145] Moreover, the NRC's official policy, at least since 1985, has been to endorse such principles:[146]

> *The issue of both insider and outsider sabotage threats will be carefully analyzed and, to the extent practicable, will be emphasized as special considerations in the design and in the operating procedures for new plants.*

However, in practice the NRC has not upheld its own policy. None of the three new reactor designs certified by the NRC in the 1990s considered how to minimize vulnerability to terrorist attack. Even after 9/11, the NRC agreed with Westinghouse that security concerns did not have to be addressed during the process for certifying the AP1000 design, but only when a utility applied for a combined construction and operating license to actually build one.

The NRC recently reconsidered this position. In September 2005, it decided to develop a new rule requiring applicants for design certification and other new reactor licensing to submit a "safety and security assessment" addressing the NRC's post-9/11 security requirements.[147] A year later the NRC staff submitted a draft proposed rule.[148] However, the commission rejected the proposal in 2007. In any event, the staff's proposal was flawed in several respects.

First, it required applicants to assess new plant designs only against the design-basis threat used

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[145] NRC, NUREG-1345, January 1981.

[146] NRC, "Policy statement on severe reactor accidents regarding future designs and existing plants," 50 FR 32138 (December 31, 1985).

[147] NRC, "Security design expectations for new reactor licensing activities," SRM-SECY-05-0120 (July 6, 2005).

[148] NRC, "Proposed rulemaking: Security assessment requirements for new nuclear power reactor designs," SECY-06-0204 (September 28, 2006).

for today's plants, which was last updated in 2003 (and formally incorporated as a change in NRC regulations in January 2007). The rationale was to be "consistent with Commission expectations that advanced reactor designs will provide at least the same degree of protection of the public and the environment that is required for the current generation of light-water reactors."[149] However, any new plant designs, if built, are likely to be operating for decades, during which time terrorist capabilities will likely grow. New plants may therefore end up being even less secure than today's generation.

Second, the draft rule required applicants asking the NRC to certify new designs to conduct a security assessment—but to incorporate only new features they consider "practicable." This standard gives applicants wide discretion to decide whether to add potentially costly security features.

Third, the rule would not have applied to designs already in the certification process when the final rule took effect, projected by the staff to be the end of FY 2007.[150] Thus, more than half the reactors already chosen by utilities planning to submit combined operating licenses—including the Advanced Boiling Water Reactor, AP1000, and ESBWR—would have been exempt from this requirement. The EPR and PBMR designs, now scheduled to be submitted to the NRC for certification in 2007, might have been exempt, depending on the submission date. (And vendors would have had strong incentive to submit their applications before the rule became effective.) Although the NRC would have encouraged such vendors to voluntarily submit security assessments, they would not have had to modify their designs.

This imprudent approach would have minimized the effectiveness and maximized the cost of nuclear plant security for decades to come. The less resistant a design is to attack, the more extensive and expensive will be the required security measures. This is particularly problematic for designs with features that reduce capital costs but increase their vulnerability to sabotage. For example, passive designs such as the AP1000 have less redundancy in safety systems and lower tolerance for equipment failures, as noted. Because the target sets are smaller, adversaries might find it easier to cause significant core damage than in existing reactors.

In fact, there is evidence that the NRC recognizes the security deficiencies of these designs. According to the draft rule,[151]

> *The Commission recognizes that developers of recent designs (such as the AP1000 and ESBWR) have conducted some type of security assessment. Another approach the Commission is considering is to require combined license applicants who reference these designs to incorporate security design features (identified by those reviews) into their combined license designs.*

This implies that the voluntary security reviews conducted for the AP1000 and ESBWR have identified security features that are clearly "practicable," in the NRC's view.

As flawed as the proposed rule was, the NRC's substitute language is even worse. It requires applicants to assess only the effects of an impact of a large commercial aircraft, and "a description and evaluation of the design features, functional capabilities and strategies to avoid or mitigate the effects."[152] Applicants do not have to consider other types of attacks, or change the plant design, no matter the outcome of the assessment. This would reduce the goal of making new plants less vulnerable to terrorist attacks to an academic exercise.[153]

Unless commercial nuclear power plants have anti-aircraft weapons or other active defenses, which is unlikely, passive structures such as containment buildings will continue to provide the only means of preventing air attacks from causing core damage. If designers of new nuclear plants

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[149] NRC, "Security design expectations for new reactor licensing activities," SECY-05-0120 (July 6, 2005).

[150] Ibid.

[151] NRC, "Proposed rulemaking: Security assessment requirements for new reactor power reactor designs, SECY-06-0204 (September 28, 2006), p. 18.

[152] Ibid.

[153] Ibid.

were required to take such threats into account, they would have to build containment structures that are more robust and protect more vital equipment than is the case today. Yet the opposite is true for the AP1000 and PBMR designs.

In contrast, the EPR was designed to meet French-German requirements that it withstand the impact of a military aircraft, as noted. This is partly why it has a double-walled containment, four well-separated safety trains, and hardened auxiliary and spent fuel buildings. Even so, the design for the EPR at Olkiluoto had to be upgraded to comply with a post-9/11 Finnish requirement that the plant be able to withstand the impact of a commercial aircraft.[154] Without a similar NRC requirement, the U.S. EPR could—and most likely would—be based on the initial, less robust design.

One NRC commissioner, Gregory Jaczko, had strongly argued that the NRC should require new plants to be able to withstand the crash of a commercial aircraft, not simply to evaluate such attacks and hope that the industry voluntarily makes changes to reduce the risks.[155] The Commission's rejection of his proposal in April 2007, unless reversed, virtually guarantees that the next generation of nuclear plants in the United States, which could be in use until the end of this century, will be unnecessarily vulnerable to 9/11-style aircraft attacks.

Recommendations:

NRC regulations that will require owners to integrate security measures into reactor designs if they are "practicable" should specify that the NRC—not reactor owners—will determine which measures meet that criterion.

The NRC should require that new reactors be able to withstand the impact of a commercial aircraft.

New Technologies and the Risks of Nuclear Proliferation and Nuclear Terrorism

As Chapter 4 noted, a major expansion of nuclear energy worldwide could increase the risks of nuclear proliferation and nuclear terrorism. In response, the DOE is developing new nuclear technologies—including reprocessing techniques and fast reactors—that it claims will have better "proliferation resistance."[156] Designers of some Generation III+ reactors also claim that they will reduce the threat of proliferation and terrorism.

However, because this is a relative measure, we need a standard for comparison. The most proliferation- and theft-resistant nuclear power system is the once-through fuel cycle now used in the United States, in which reactors are fueled with low-enriched uranium, and the spent fuel is disposed of directly.[157] However, this is not the standard used by the DOE, which instead assesses proliferation resistance by comparing it to a fuel cycle using PUREX reprocessing technology.

In fact, no technical fix can remove the proliferation risks associated with reprocessing and the use of plutonium-based fuel. Once separated from highly radioactive fission products, the plutonium is vulnerable to theft or diversion.

New reprocessing technologies will leave the plutonium in a mixture with other elements, but these are not radioactive enough to provide theft-resistance, and a nation seeking nuclear weapons could readily separate the plutonium from the other elements by chemical means. And some of these other elements are themselves usable in weapons.

Finally, the use of these "proliferation-resistant" technologies would reduce the ability of commercial-scale reprocessing and fuel production facilities to accurately account for the material they handle—making the already formidable task of detecting the diversion or theft of bomb-usable quantities of plutonium even harder.

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[154] Areva NP, "Finnish EPR Olkiluoto 3," brochure (2006), p. 14, online at *http://www.areva-np.com/common/liblocal/docs/press/OL3_EPR_press%20kit__06_06_en.pdf.*

[155] Commissioner Jackzo's comments on SECY-06-0219, "Final rulemaking to revise 10 CFR 73.1, Design Basis Threat requirements" (December 13, 2006).

[156] The DOE defines this as "the degree of difficulty of using, or of diverting material from, a commercial reactor and fuel cycle system for the clandestine production of materials usable in nuclear weapons." U.S. DOE, Nuclear Energy Research Advisory Committee TOPS Task Force, "Technical opportunities to increase the proliferation resistance of global civilian nuclear power systems" (January 2001).

[157] Marvin Miller, "Attempts to reduce the proliferation risks of nuclear power: Past and current initiatives," in *Nuclear power and the spread of nuclear weapons: Can we have one without the other?* P. Leventhal, S. Tanzer, and S. Dolley, eds. (Dulles, VA: Brassey's, 2001), p. 143.

WEIGHING THE CLAIMS FOR GENERATION III+ REACTORS

Reprocessing is not necessary for most Generation III+ reactors, as they can use fuel made with low-enriched uranium. Like today's reactors, these reactors would meet the once-through standard, provided their spent fuel is not reprocessed. However, some reactor vendors claim that their designs are more proliferation-resistant than today's reactors. These claims appear to be overstatements.

For example, promoters of the PBMR claim it is more proliferation-resistant because the spent fuel is unlikely to be reprocessed, for two reasons. First, because the fuel can achieve very high "burn-ups"—that is, it can be irradiated for a long time before being replaced—much of the energy content will be used, and there will be little incentive to reprocess it. Second, the fuel is more difficult to reprocess than that from standard light-water reactors.

However, while a higher burn-up would increase the reactor's fuel efficiency, it is not clear that it would dissuade reprocessing. Because the large amount of graphite in the spent fuel increases the spent fuel volume by at least a factor of 10 relative to spent fuel from light-water reactors, it would pose significant waste storage and disposal concerns, and could provide an incentive to reprocess the spent fuel so the graphite could be separately managed. In fact, the DOE is already sponsoring R&D on the reprocessing of spent fuel from gas-cooled reactors such as the PBMR.[158] On balance, it is unclear whether the DOE would favor reprocessing PBMR fuel if these reactors are built.

Developers of reactors with long-life cores, such as IRIS, point to the fact that refueling would occur less often than for conventional reactors, and argue that this would reduce access to spent fuel.[159] However, fewer shutdowns would have a marginal effect on proliferation, because the risk that highly radioactive spent fuel will be stolen or diverted is already low.

Supporters argue that the IRIS reactor's fuel lifetime of up to eight years would make it proliferation-resistant, as infrequent refueling would give nations fewer opportunities to gain access to the plutonium-bearing spent fuel. (Conventional light-water reactors are typically refueled every 18 months.) To achieve the eight-year lifetime, the reactor would require uranium that is more highly enriched than that used in conventional reactors—5 percent U-235 for the first reactor core, and 9 percent for successive cores. (Because the NRC has licensed only fuels enriched up to 5 percent U-235, the first IRIS reactor would have a four-year core with fuel enriched to 4.95 percent,[160] and even this fuel may be difficult to license because it will have a high burn-up rate.)

Moreover, if a nation planned to reprocess spent fuel to produce plutonium for weapons, it would have no reason to wait until a scheduled refueling. The country could withdraw from the Non-Proliferation Treaty and remove the fuel at any time. Longer fuel cycles also require fuel with higher-enriched uranium than used in reactors today.[161] This could make the fresh fuel a more desirable feed material for clandestine production of highly enriched uranium for bombs.

A much more important consideration than refueling frequency is whether a reactor uses fuel based on low-enriched uranium or plutonium. The developers of IRIS are also considering MOX fuel, with plutonium concentrations exceeding 20 percent.[162] Thus the fresh fuel would be highly attractive as a source of plutonium for use in weapons,

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[158] Barry B. Spencer et al., Oak Ridge National Laboratory, "Processing of spent TRISO-coated GEN IV reactor fuels," Eighth Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, November 9–11, 2004, Las Vegas, NV.

[159] "Nuclear energy: Assuring future energy supplies," *Oak Ridge National Laboratory Review* 35, 2 (2002), online at *http://www.ornl.gov/info/ornlreview/v35_2_02/assuring.shtml*; and M. Carelli, "IRIS: A global approach to nuclear power renaissance," *Nuclear News*, September 2003, p. 32–42, online at *http://hulk.cesnef.polimi.it/Papers/NuclearNews-sept2003-IRIS+cover.pdf*.

[160] Mario D. Carelli, "IRIS: A global approach to nuclear power renaissance," *Nuclear News*, September 2003, p. 32, online at *http://hulk.cesnef.polimi.it/Papers/NuclearNews-sept2003-IRIS+cover.pdf*.

[161] DOE, Nuclear Energy Research Advisory Committee (NERAC), and Generation IV International Forum (GIF), "Generation IV roadmap: Description of candidate water-cooled reactor systems report, GIF-015-00 (December 2002), p. 58.

[162] M. Carelli, "IRIS: A global approach to nuclear power renaissance," *Nuclear News*, September 2003, p. 38, online at *http://hulk.cesnef.polimi.it/Papers/NuclearNews-sept2003-IRIS+cover.pdf*.

and with a MOX fuel cycle, this reactor would be much less proliferation-resistant, even if the reactor is refueled less often.

The authors of a DOE-sponsored report also claim that reprocessing fuel from reactors with long-lived cores would entail fewer proliferation and terrorism risks, because the longer the fuel is burned, the less desirable the mixture of plutonium isotopes for making nuclear weapons.[163] However, this argument is incorrect, as made clear in an authoritative statement from the DOE itself in 1998.[164] Nearly all isotopic mixtures of plutonium can be used in nuclear weapons, and there is no meaningful difference in the ease with which someone could make a nuclear bomb from plutonium produced in a long-life core reactor like IRIS and that produced in a conventional light-water reactor. This is true for both advanced nuclear weapons states and unsophisticated terrorist groups. It is astonishing that some continue to use this argument, and that it appeared in a DOE-sponsored document.

The claims for the 4S reactor are similar to those for IRIS. Toshiba describes the reactor as proliferation-resistant because it would be neither refueled nor readily accessible, as it would sit in a sealed vault 30 meters underground. Because the 4S would have a higher enrichment than the IRIS fuel (17 to 19 percent LEU instead of 9), it would be even more attractive as a feedstock for producing HEU for weapons.

THE GLOBAL NUCLEAR ENERGY PARTNERSHIP

In 2006, the Bush administration announced the Global Nuclear Energy Partnership (GNEP). A major focus of GNEP is developing and deploying commercial-scale reprocessing plants and advanced fast reactors in the United States and select countries abroad. Fast reactors cannot be fueled with low-enriched uranium, but require either highly enriched uranium or plutonium.

Despite the use of such bomb-usable fuels, the goal of GNEP is to facilitate the growth of nuclear energy worldwide while decreasing the risk of proliferation:[165]

> *GNEP seeks to bring about a significant, wide-scale use of nuclear energy, and to take actions now that will allow that vision to be achieved while decreasing the risk of nuclear weapons proliferation . . . GNEP will advance the nonproliferation and national security interests of the United States by reinforcing its nonproliferation policies and reducing the spread of enrichment and reprocessing technologies, and eventually eliminating excess civilian plutonium stocks that have accumulated.*

At the center of the GNEP plan are a nuclear fuel recycling center, a large reprocessing facility that can handle 2,000–3,000 metric tons of spent fuel each year, and many advanced recycling reactors: large, fast neutron reactors with a power rating of 100–800 MW that would be fueled with plutonium from reprocessed spent fuel. At first, the recycling center would use a PUREX-like reprocessing technology. These facilities would increase the risks of proliferation and nuclear terrorism, as they would not meet the “once-through” standard of protection provided when plutonium remains embedded in large, highly radioactive spent fuel rods until disposed of in a geologic repository.

NEW REPROCESSING TECHNOLOGIES

GNEP also includes an R&D program to develop “proliferation-resistant” reprocessing technologies that will be less vulnerable to diversion or theft than the PUREX technology.

This program will focus on a group of aqueous separation technologies known as UREX+

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[163] DOE, Nuclear Energy Research Advisory Committee (NERAC), and Generation IV International Forum (GIF), “Generation IV roadmap: Description of candidate water-cooled reactor systems report,” GIF-015-00 (December 2002), p. 58.

[164] DOE, Office of Arms Control and Nonproliferation, “Nonproliferation and arms control assessment of weapons-usable fissile material storage and excess plutonium disposition Alternatives,” DOE/NN-0007 (1997), pp. 37–39.

[165] DOE, “Global nuclear energy partnership strategic plan” (2007), pp. 1–10.

and a non-aqueous separation technology known as "pyroprocessing," or "electrometallurgical treatment." UREX+ would be used to reprocess light-water reactor fuel, and could also be used to reprocess oxide-based spent fuel from fast reactors. Pyroprocessing would be used for either oxide or metal spent fuel from fast reactors.

The DOE claims that these technologies are proliferation-resistant because, unlike PUREX, they do not separate the plutonium from the rest of the spent fuel. As Secretary of Energy Samuel Bodman said in November 2005, "In addressing reprocessing . . . we are guided by one overarching goal: to seek a global norm of no separated plutonium. I think everyone would agree that the stores of plutonium that have built up as a result of conventional reprocessing technologies pose a growing proliferation risk that requires vigilant attention."[166] However, although Secretary Bodman's concerns are justified, the DOE's proposed solution is problematic.

One variant the DOE is pursuing, UREX+1a, would keep plutonium in a mixture with other actinides (neptunium, americium, and curium) and lanthanides (such as cerium and europium), which are more radioactive than plutonium. Similarly, pyroprocessing can be used to extract a mixture of plutonium, other actinides, uranium, and some lanthanides (primarily cerium-144). However, these approaches would provide no meaningful advantage over PUREX, because the properties of the mixed products would be very similar to those of plutonium alone. This material would therefore be neither more difficult to steal than plutonium produced by PUREX nor more difficult to process for use in a nuclear weapon.

While neptunium, americium, and curium are more radioactive than plutonium, these elements generate a dose rate of less than one rad per hour at a distance of one meter.[167] This dose rate is a hundred times less than that required for spent fuel to be self-protecting, and a thousand times less than that generated by spent fuel 50 years after it has been discharged from the reactor. (The self-protection standard is 100 rads per hour at one meter, which would be lethal to anyone at a distance of one meter in less than an hour.) As is the case for pure plutonium, this plutonium mixture would emit far too little radiation to cause immediate harm to anyone who stole it, and could be handled without heavy shielding or robotic tools.

The plutonium could be separated from the other elements in the mixture using conventional chemical techniques, and then used to make nuclear weapons. However, there might be no need to do so. According to a report from a 1999 workshop at the DOE's Lawrence Livermore National Laboratory (LLNL), the transuranic elements or other actinides in spent fuel could be used to build nuclear weapons:

> *Examination of various cycles and the opinions of weapons-design experts lead to the conclusion that there is no 'proliferation-proof' nuclear power cycle. Explosive Fissionable Material (EFM) includes most of the actinides and their oxides.*[168]

Dr. Bruce Goodwin of LLNL also maintained at the workshop that "as nuclear weapons design and engineering expertise combined with sufficient technical capability become more common in the world, it becomes possible to make nuclear weapons out of an increasing number of technically challenging explosive fissionable materials."[169] In other words, it is unwarranted to assume that terrorists could not acquire the ability to build nuclear weapons with the mixture of plutonium and other actinides produced by UREX+.

Of course, none of these reprocessing technologies meet the once-through standard for resistance to proliferation and nuclear terrorism. As the DOE declared in response to questions from Congressman Edward Markey in 2006, "The

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[166] Remarks prepared for Secretary Bodman, 2005 Carnegie International Nonproliferation Conference, Washington, DC, November 7, 2005.

[167] E.D. Collins, Oak Ridge National Laboratory, "Closing the fuel cycle can extend the lifetime of the high-level-waste repository," American Nuclear Society 2005 Winter Meeting, Washington, DC, November 17, 2005, p. 13.

[168] Lawrence Livermore National Laboratory, Center for Global Security Research, "Proliferation-resistant nuclear power systems: A workshop on new ideas" (June 2–4, 1999, March 2000), p. 7, online at *http://www.llnl.gov/tid/lof/documents/pdf/238172.pdf.*

[169] Ibid, p. 14.

plutonium mix from UREX+ would not meet the self-protection standard of spent fuel and, therefore, the physical protection measures and safeguards associated with the process will need to be stringent."[170]

The fact that highly radioactive neptunium-237 and americium isotopes would be part of the mix would not mean that it would require less protection than pure plutonium, because these materials can also be used to make nuclear weapons. According to DOE guidelines, separated neptunium-237 and americium must be "protected, controlled and accounted for as if they were SNM [special nuclear material]"—in this case, as if they were highly enriched uranium.[171]

THE CHALLENGES OF TRACKING PLUTONIUM

While the reprocessing modifications proposed under GNEP would not significantly increase the theft resistance of plutonium, they would likely reduce the accuracy with which plant operators and international inspectors would be able to track the plutonium—which is the most important means of safeguarding against diversion.

In a reprocessing facility, operators account for the amount of plutonium they are handling in two ways. First, they do so indirectly, by measuring alpha and neutron emissions from the mixtures being handled. However, the other actinides in GNEP plutonium mixtures also emit alpha particles and neutrons, making it difficult to determine the precise amount of plutonium. Second, operators take samples of some in-process materials to measure the amount of plutonium directly. Including highly radioactive material in the plutonium mixture, as proposed, would increase the hazards and complexities of collecting these samples.[172]

Recent DOE guidance also requires operators to track the amounts of the minor actinides neptunium and americium as stringently as weapons-usable uranium-235. Because the precision of standard measurement techniques is expected to be much lower for the minor actinides than for plutonium, the overall measurement precision of weapons-usable isotopes will decrease.[173]

The many fuel separation cycles and fuel fabrication plants contemplated under the proposed GNEP scheme would compound these challenges. In one version of the fuel cycle circulated by Argonne officials, spent fuel from light-water reactors would be reprocessed at large, centralized UREX+ plants to extract a product containing plutonium, minor actinides, and lanthanides.

The product would then be shipped as oxide around the country to multiple fast reactors (advanced recycling reactors), each with its own metallic spent fuel pyroprocessing and fuel fabrication plant. (The lanthanides, cerium-144 and europium-154, would remain in the product for transport because the radiation barrier provided by the actinides alone would not protect the mixture from theft or diversion.)

At each site, the lanthanides would be removed at small aqueous separation plants, and the remaining product fed into the fuel fabrication plant, along with the plutonium and actinides recovered by pyroprocessing. Thus each advanced recycling reactor would also have an aqueous separations plant, a pyroprocessing plant, and a fuel fabrication plant.

About three advanced recycling reactors would be required to use the annual production of plutonium and actinides from about four light-water reactors of the same power rating (about 1 MT). Thus, if total U.S. generating capacity of light-water reactors remained at 100 GWe, some 75 1-GWe light-water reactors would be needed. Even if four reactors were located at one site, some 20 sites would contain multiple facilities requiring

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[170] DOE, response #18 to questions for the record from Rep. Edward Markey (D-MA), House Energy and Commerce Committee, March 9, 2006.

[171] DOE, "Nuclear material control and accountability," DOE M 470.4-6 (August 26, 2005).

[172] According to Los Alamos scientists, "Even small concentrations of MAs [minor actinides] in plutonium mixes could complicate the accuracy of the plutonium measurement if not properly taken into account: consequently, safeguards of plutonium could be affected." J.E. Stewart et al., "Measurement and accounting of the minor actinides produced in nuclear power reactors," LA-13054-MS (January 1996), p. 21, online at *http://www.sciencemadness.org/lanl2_a/lib-www/la-pubs/00255561.pdf.*

[173] Ibid, pp. 16–17.

Box 9. A Truly Proliferation-Resistant Reprocessing Technology?

It is possible to develop a reprocessing technology that would keep enough highly radioactive fission products in the plutonium mixture to provide a radioactive barrier comparable to that of spent fuel, thus making the mixture theft-resistant. However, developing a reprocessing technology that would not also make it easier for nations to produce material for nuclear weapons is far more difficult.

Previous attempts to develop such a technology have failed. In 1978, U.S. and U.K. scientists announced the development of Civex, "a method of reprocessing spent fuel from atomic power plants that would not produce pure plutonium, which could be used to make atomic bombs."[174] Unlike UREX+ or pyroprocessing, Civex was designed to keep a significant fraction of the highly radioactive fission product cesium-137 with the plutonium.

According to the developers, "In the Civex process, spent fuel would be treated so that it could be reused as fuel . . . but the plutonium in it would not at any stage be purified to the extent that it could be used for a bomb . . . the fuel, at every stage of the process, would be so highly radioactive that it could not be handled directly by human beings, a fact that would presumably deter terrorists from attempting to steal the material."[175]

Even so, the General Accounting Office (now the Government Accountability Office) found that while Civex and similar approaches might help protect the plutonium against terrorist theft, they would have little impact on diversion by states.

After separating plutonium and uranium, the Rokkasho-mura reprocessing plant in Japan mixes the two streams together again to produce a 50/50 mixture of plutonium and uranium. However, this mixture is no more self-protecting than pure plutonium, and the plutonium is readily separated from the mixture using bench-type fume-hood facilities.

Moreover, according to recent research at the DOE's Oak Ridge National Laboratory, including highly radioactive fission products with the plutonium would "increase significantly the costs of fuel fabrication and transportation."[176] Such a mixture would also be more dangerous to handle and process into new reactor fuel. Thus the material would probably need to be purified later before it could be used to make new fuel, which would again make it vulnerable to theft and diversion.

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[174] Facts on File, World News Digest, "New reprocessing technique announced" (March 3, 1978).

[175] Ibid.

[176] E.D. Collins, Oak Ridge National Laboratory, "Closing the fuel cycle can extend the lifetime of the high-level-waste repository," American Nuclear Society 2005 Winter Meeting, November 17, 2005, Washington, DC, p. 13.

domestic (and perhaps international) safeguards. Resolving the accounting anomalies in this complex network—given the reduced precision of the sampling techniques—would be a formidable task.

Recommendation:

The United States should reinstate a ban on reprocessing U.S. spent fuel, and actively discourage other nations from pursuing reprocessing.

Fast Reactors and Nuclear Waste

A major selling point of the proposed GNEP is that it will use fast reactors to burn up highly radioactive actinides, thus greatly reducing the amount of nuclear waste requiring disposal in a geologic repository. Supporters of this approach say one of the goals is to "optimize the use of the first repository" and "reduce the need for, or avoid a second repository."[177] In fact, Deputy Secretary of Energy Clay Sell has repeatedly testified that unless the U.S. implements the GNEP program,

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[177] Ralph Bennett, director of advanced nuclear energy, Idaho National Energy and Environmental Laboratory, "AFCI systems analysis overview," presentation at AFCI Semi-Annual Review Meeting (August 28, 2003), p. 3.

it will need nine geologic repositories the size of Yucca Mountain to dispose of the spent fuel that will be generated by the year 2100, assuming that U.S. nuclear capacity rises from about 100 reactors today to about 600 in 2100.[178]

The DOE has argued that such an "actinide recycle" system could ultimately increase repository capacity by a factor of 50 to 100.[179] This could potentially enable the United States not only to dispose of high-level waste from a greatly expanded domestic nuclear energy program, but also to dispose of high-level waste from other countries that have leased U.S. fuel under GNEP, according to Assistant Secretary of Energy Dennis Spurgeon.[180]

In addition to capacity, there is also the issue of how long any geologic repository must remain intact. As noted, the EPA was expected at press time to issue revised standards that would require regulating the radiation dose to the public for 1 million years after Yucca Mountain closes—a standard that simply may be impossible to meet, given limits in today's modeling techniques. In response, the DOE has claimed that an actinide-burning system would reduce the toxicity of the waste in a repository, so the peak radiation dose would occur within a thousand years rather than within a million, which could simplify licensing.[181]

Various claims made by proponents about the potential of GNEP to increase the capacity of Yucca Mountain by 10 to 100 times appear to stem from a single article by a group of Argonne scientists headed by Roald Wigeland, published in the April 2006 issue of *Nuclear Technology.*[182] These scientists calculated the increase in waste density that could be achieved by removing highly radioactive actinides, which generate a lot of heat, based on how efficiently the actinides could be separated from the other waste.

Scientists now believe there are two limits on the amount of heat the waste placed in a geologic repository can generate: one short-term (hundreds of years) and one longer-term (thousands of years). The longer-term limit is less restrictive. To achieve the greatest gains and stay below the longer-term limit, the actinides plutonium, americium, and curium must be removed from the waste with high separation efficiency. To achieve further gains without exceeding the short-term limit, the relatively short-lived fission products cesium-137 and strontium-90 (which have a 30-year half-life) must also be removed.

Neptunium-237 is not a major heat-generating radionuclide. However, it, too, would have to be removed from the waste in a more densely packed repository to ensure that the peak radiation dose occurs within a thousand years, as it would contribute the most radiation to the dose received by someone exposed to the waste after 10,000 years.

Clearly, if heat-generating radionuclides can be extracted from spent fuel, then more residual waste can be packed into a heat-limited repository. However, simply removing cesium, strontium, and actinides from spent fuel will accomplish nothing unless these materials are also safely stored. Because cesium-137 and strontium-90 produce most of the decay heat from spent fuel in the short run, they must be actively cooled for two or three centuries, or provided with passive cooling—like that provided by the dry casks now used to store spent fuel. Because the amount of waste in dry casks is also limited by the amount of heat the waste generates, dry-cask storage for cesium-137 and strontium-90 would be similar to that for spent fuel.

The DOE argues that cesium-137 and strontium-90 can be placed in 300-year "decay storage." However, simply storing intact spent fuel for 300

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[178] Under a statutory limit, Yucca Mountain can accept up to 70,000 metric tons of heavy metal.

[179] DOE, "Minimize nuclear waste" fact sheet, online at *http://www.gnep.energy.gov/gnepMinimizeNuclearWaste.html.*

[180] Dennis Spurgeon, remarks to National Research Council committee reviewing the DOE's Research & Development Program, Office of Nuclear Energy, Science & Technology, Washington, DC, January 9, 2007.

[181] Testimony of Samuel Bodman, secretary of energy, at a hearing of the Senate Energy and Natural Resources Committee, February 9, 2006.

[182] R. Wigeland, T. Bauer, T. Fanning, and E. Morris, "Separations and transmutation criteria to improve utilization of a geologic repository," *Nuclear Technology* 154 (April 2006):95–106.

years before disposal would be far less expensive and risky than removing cesium-137 and strontium-90 and storing them separately. (Although intact spent fuel would not remain highly radioactive, and thus self-protective, for 300 years, very large and heavy spent fuel assemblies would still restrict access to the plutonium.)

Furthermore, to achieve the DOE's goal of an increase in repository capacity by a factor of 50 to 100, the plutonium, neptunium, and other long-lived actinides in reactor fuel must be almost completely fissioned. Yet each reactor cycle consumes only a small fraction of these elements. To reduce them by a meaningful amount, the spent fuel must be reprocessed and reused repeatedly over many years. If this system shuts down at some point, the remaining actinides will have to be disposed of in a repository anyway. An enormous amount of money would have been spent for a relatively modest benefit.

A comprehensive 1996 study by the National Academy of Sciences (NAS) has shown that an actinide recycle system that would employ fast reactors would not be able to attain this goal in a reasonable period of time. The study also found that to have even a chance of meeting its goals, an actinide recycle system would require an extraordinary engineering effort.[183]

But even if such a transmutation system could be built, coordinated, and operated, it would be very expensive, and have to run for a long time. Under a scenario in which the amount of U.S. nuclear power falls, and the total inventory of spent fuel is 62,000 metric tons (compared with about 60,000 metric tons in 2007), the NAS concluded that a fast reactor system (with a 0.65 breeding ratio[184]) would cost some $500 billion and require about 150 years.

If the amount of nuclear power remained constant, the NAS found that:

> *The . . . operating time required to reduce the inventory of residual TRUs* [transuranic elements] *to even 1% of the inventory of the . . . LWR once-through fuel cycle would be unrealistically long, on the order of many millenia. The first century of constant-power transmutation could only reduce the inventory fraction to about 14%.*

The NAS did not evaluate a scenario in which the amount of nuclear power rises. However, the DOE recently assessed the economics of its GNEP plan given a roughly six-fold increase in U.S. nuclear energy by 2100.[185] In that case (which used the same breeding ratio assumed by the NAS), the system reduced the amount of transuranics by only about 50 percent after 100 years, compared with the direct-disposal fuel cycle.[186] And the DOE study found that the cost of achieving this reduction would be more than twice the cost of direct disposal alone—translating to an additional cost of more than $750 billion.[187]

But the DOE study does not compare apples to apples, because it charges the direct-disposal scenario with the full cost of 12 large geologic repositories, but does not charge the GNEP scenario with the cost of disposing of the 51 percent of the actinide inventory that remains in the fuel cycle. The DOE also assumes that 100 years from now, institutions will be in place to ensure that

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[183] "The S&T [separation and transmutation] of TRUs [transuranic elements] and certain long-lived fission products in spent reactor fuel is technically feasible and could, in principle, provide benefits to radioactive waste disposal in a geologic repository. However, to begin to have a significant benefit for waste disposal, an entire S&T system consisting of many facilities would have to operate in a highly integrated manner from several decades to hundreds of years. The deployment of an S&T system that is extensive enough to have a significant effect on the disposition of the accumulated LWR spent fuel would require many tens to hundreds of billions of dollars and take several decades to implement.

"Merely developing, building and operating the individual components of the system would give little or no benefit. To have a real effect, an entire system of many facilities would be needed in which all the components operate with high reliability in a synchronized fashion for many decades or centuries . . . the magnitude of the concerted effort and the institutional complexity . . . are comparable to large military initiatives that endure for much shorter periods than would be required." National Academy of Sciences, *Nuclear wastes: Technologies for separations and transmutation* (Washington, DC: 1996), p. 81, online at *http://www.nap.edu/books/0309052262/html*.

[184] The breeding ratio is a measure of the number of plutonium atoms produced for each atom fissioned in a reactor core. Fast breeder reactors aim for breeding ratios greater than one. Fast burner reactors, which are intended to consume plutonium, have breeding ratios of less than one.

[185] Matthew Crozat, "Evaluating the economics of GNEP deployment," DOE, pre-decisional draft (January 8, 2007).

[186] Ibid, p. 5.

[187] Ibid. Crozat calculates that the additional price for avoiding 11 geologic repositories and eliminating 49 percent of transuranic elements is around $2.7/MWh. One can estimate that about 280 billion MWh of nuclear electricity is generated in 100 years under his scenario.

the GNEP system will remain fully functional. Without that guarantee, there can be no assurance that the remaining heat-bearing actinides could be managed safely. And the only way to provide such assurance would be to dispose of those elements in six geologic repositories. This would cost another several hundred billion dollars—for a total cost of more than $1 trillion (undiscounted) for the GNEP option, compared with direct disposal.

This last challenge underscores the fact that the GNEP proposal does not satisfy a fundamental ethical principle for the disposal of nuclear waste: intergenerational equity. This principle can be summarized as follows:[188]

- The liabilities of waste management should be considered when undertaking new projects.
- Those who generate the wastes should take responsibility, and provide the resources, for managing these materials in a way that will not impose undue burdens on future generations.
- Wastes should be managed in a way that secures an acceptable level of protection for human health and the environment, and affords to future generations at least the level of safety acceptable today.
- A waste management strategy should not assume a stable social structure in the indefinite future, nor technological advances. Rather, it should aim to bequeath a passively safe situation: that is, one that does not rely on active institutional controls to maintain safety and security.

Direct disposal of spent fuel in a geologic repository that can contain the waste without active intervention is the epitome of a system that meets the principle of intergenerational equity. Although such a repository has not yet been licensed, the scientific consensus is that it is feasible. In contrast, GNEP requires a complex system of dangerous facilities that must be operated and repeatedly rebuilt for centuries. These facilities include those that allow aboveground "decay storage" of short-lived fission products, and a host of added facilities needed to reprocess and fission highly radioactive actinides. This system clearly fails to meet fundamental criteria for responsible waste management.

Recommendation:

The United States should eliminate its programs to develop and deploy fast reactors.

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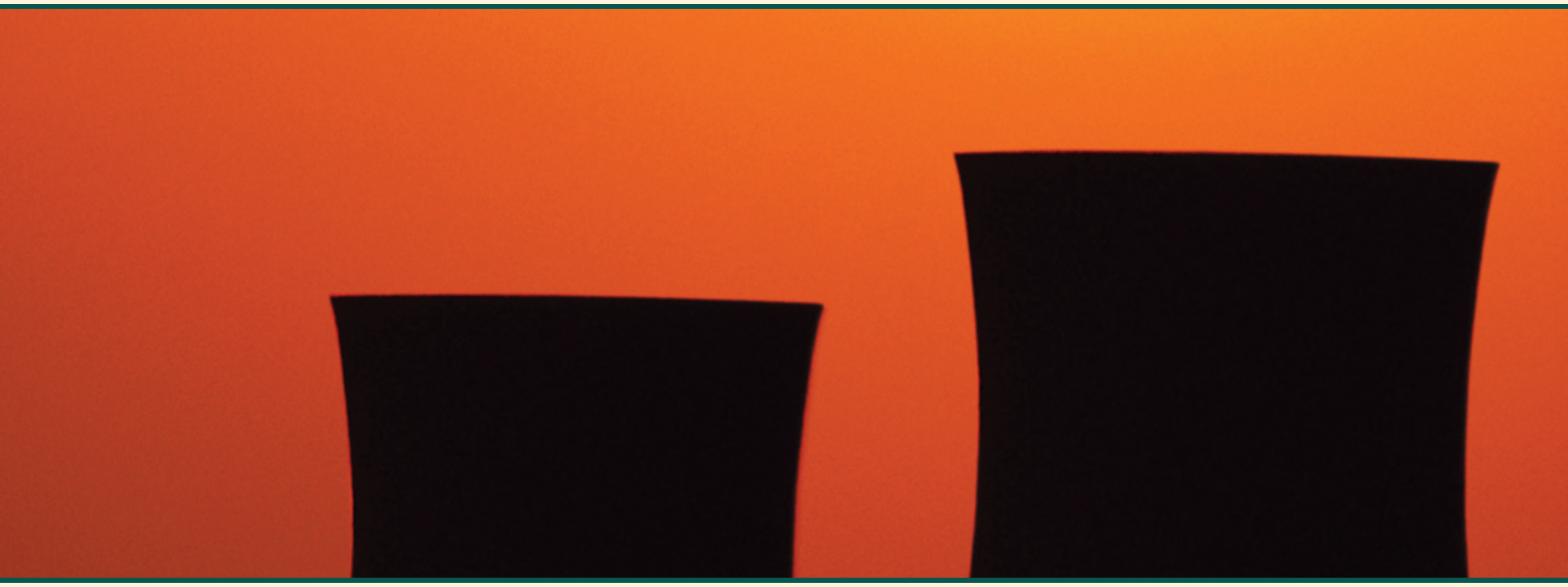
[188] Nuclear Energy Agency, "The environmental and ethical basis of geologic disposal of long-lived radioactive wastes" (Paris: Organisation for Economic Co-operation and Development, 1995).

NUCLEAR POWER IN A WARMING WORLD

Assessing the Risks, Addressing the Challenges



Global warming demands a profound transformation in the ways we generate and use energy. Because nuclear power results in few global warming emissions, an increased number of nuclear power plants could help reduce global warming—but could also increase the threats nuclear power poses to our safety and security. This report assesses these risks and proposes concrete ways to minimize them.

The Union of Concerned Scientists (UCS) has identified steps the United States can take to make nuclear power safer, improve the security of reactors against sabotage and terrorist attacks, minimize the risk that nuclear power will make it easier for other nations and terrorist groups to acquire nuclear weapons materials, and deal with the radioactive waste from power plants. These steps are pragmatic and doable—and their implementation is vital if nuclear power expands in the United States or worldwide. They include improving government oversight of nuclear power safety, upgrading security standards for reactors, providing secure interim storage for nuclear waste and identifying additional potential sites for a geologic repository, and reinstating a ban on reprocessing and working to eliminate reprocessing worldwide and place international controls on uranium enrichment.

UCS also examined new reactor designs under consideration in the United States and found that only one appears to have the potential to be significantly safer and more secure than today's reactors.

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