Matthew Bunn and Martin B. Malin

Enabling a Nuclear Revival— And Managing Its Risks

As John Holdren points out in the introduction to this *Innovations* special issue, the world will need to produce huge quantities of energy in the 21st century to meet the needs of a growing world population, while also working to lift billions of people out of poverty. Providing this energy at a reasonable cost, without causing unmanageable climate disruption, security risks, or other environmental devastation, will be one of the century's most daunting challenges. This challenge will be even more difficult to meet if nuclear energy does not play a substantial part. But achieving the scale of nuclear energy growth required while managing the risks of that growth will be a major challenge in itself, one that will require both technical and institutional innovations.

Consider the scale of growth that is needed for nuclear energy to make a meaningful contribution to mitigating carbon emissions. One oft-cited 2004 analysis broke down the problem of shifting away from a business-as-usual energy path into seven "wedges"—different technologies that would each grow to displace a billion tons of carbon emissions per year by 2050 (see Figure 1).[1] More recent science suggests that 10 to 15 such wedges are likely to be required, as business-as-usual emissions are higher than previously projected, the carbon-absorbing properties of the oceans appear to be weaker, and the atmospheric concentration of carbon required to avoid disastrous climate consequences seem to be even lower than once thought. For nuclear power to provide even *one* such wedge would require a

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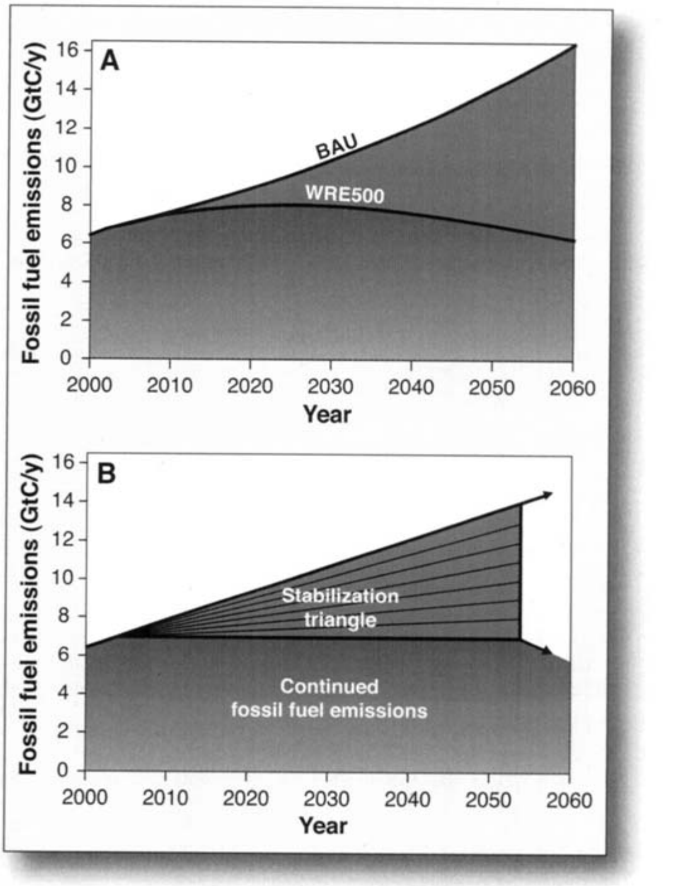

Figure 1. Stabilization Wedges.

Source: S. Pacala and R. Socolow "Stabilization Wedges," Science, Vol. 305, 13 August 2004, p. 969. "BAU" refers to the "business as usual" scenario, which project ever-increasing carbon emissions; "WRE500" refers to one particular emissions path for stabilizing atmospheric concentrations of greenhouse gases at 500 parts per million of carbon dioxide.

tripling of global nuclear capacity by 2050, while simultaneously replacing nearly all the reactors now operating as they reach the end of their useful lives. This would entail increasing the pace of construction from four nuclear plants connected to the grid each year worldwide—the current rate—to 25 plants on average every year for the next 40 years. Since there is no possibility that rate of growth will be achieved in the next few years, the pace at the end of the period would have to be still higher, in the range of 30 to 50 reactors per year worldwide.[2]

To achieve this level of growth, nuclear energy must become dramatically more attractive to utilities, governments, and publics around the world. This would require reducing costs, preventing any substantial accident, avoiding terrorist sabotage, finding politically sustainable solutions to nuclear-waste management, and ensuring that nuclear energy does not contribute (and is not seen as contributing) to the spread of nuclear weapons to proliferating states or terrorist groups.

Moreover, these challenges are interconnected and can only be addressed effectively in an integrated fashion. For example, we must take measures to improve nuclear safety and security that are also affordable, and we have to find acceptable ways of disposing of waste without increasing proliferation risks.

In short, nuclear safety, security, nonproliferation, and waste management are essential enablers for large-scale nuclear energy growth. It is very much in the world's interest—and the nuclear industry's interest—to drive the risk of catastrophe as close to zero as possible. Even a single catastrophe—whether a Chernobyl-scale accident, a successful sabotage (a "security Chernobyl"), or, worse yet, a terrorist nuclear bomb—would doom any prospect for nuclear growth on the scale needed to make a significant contribution to coping with climate change.

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Although continued R&D on new technologies is important, the most critical near-term steps to reduce the risks from nuclear energy and to improve its chances of playing a major role in mitigating climate change will be institutional, not technical. For the long term, new reactor and fuel-cycle designs that are cheaper, safer, more easily secured, more proliferation resistant, and more appropriate for developing countries with modest electricity grids and technical infrastructures could have a major impact on nuclear energy's role in carbon mitigation. But even as low-risk new technologies come on line, the global risk of an accident or sabotage is likely to be dominated by a handful of facilities—those without the new safety and security features, and those in countries with weak safety and security regulations and poorly trained staff who cut corners on safety and security rules. Stronger global institutions and agreements are needed now to identify and remedy problems at the highest-risk facilities; greater international cooperation will be a necessary and essential part of a peaceful and vibrant nuclear future.[3]

This section of the *Innovations* special issue presents three particular institutional innovations now being pursued that could make a real difference for the future of nuclear energy and potentially for the planet. Tariq Rauf and Zoryana Vovchok describe current efforts to establish an international "bank" for nuclear fuel, giving countries guaranteed fuel supplies without having to build their own plants to enrich uranium (plants that could also be used to produce more highly enriched uranium for use in nuclear weapons). Roger Howsley describes the recently established World Institute for Nuclear Security (WINS), designed to promote stronger nuclear security practices worldwide. Charles McCombie outlines the possibility of regional or international management of spent nuclear fuel or nuclear waste, avoiding the risks and costs of every country with even one nuclear power plant establishing its own nuclear waste disposal site laden with plutonium-bearing spent fuel—and potentially creating strong incentives for countries to rely on international fuel supplies, rather than building their own enrichment and reprocessing plants to produce and manage their nuclear fuel. In what follows we provide an overview of some of the innovations that must be put in place to enable future nuclear growth and to manage the resulting safety, security, and proliferation risks.

IMPROVING SAFETY

Nuclear plants today are dramatically safer than they were in the days of Three Mile Island and Chernobyl.[4] But the 2002 incident at the Davis-Besse plant in the United States—where dripping boric acid ate away a football-sized hole in the reactor pressure vessel head before it was discovered—is a potent reminder that nuclear safety requires constant vigilance. Safety must continue to improve. Tripling nuclear energy capacity by 2050 without increasing the risks of a nuclear accident would require that the per-reactor annual accident risk be reduced by a factor of three compared to today's. Efforts to improve safety must focus particularly on identifying and addressing the least safe facilities, which are likely to dominate the global accident risks; these least-safe facilities are likely to be concentrated in three categories.

First, aging first-generation designs still pose significant safety risks that need to be addressed. (Remarkably, a dozen reactors with the same design as Chernobyl are still operating, for example; although a number of steps have been taken to avoid a repeat of that accident, these reactors still lack modern containment vessels and emergency core cooling systems.) Extending licenses and boosting the designed power output in existing plants may be desirable for carbon mitigation and profitable for the operators of those facilities, but such extensions must not be granted without ensuring that every necessary step has been taken to ensure that these reactors do not pose a substantially higher risk of a catastrophic radiation release than more modern facilities. Those that cannot meet that goal should be shut down.

Second, there is the problem of "newcomer" countries that do not yet have experience operating an effective nuclear regulatory system, building a sound nuclear-safety culture, or providing trained and capable personnel. A major effort will be necessary to help these countries put effective safety measures in place. One approach that should be considered would focus on small, factory-built reactors with high levels of built-in safety and security, which could be deployed at a site and generate electricity for 10-20 years with few staff members on site, an approach sometimes referred to as the nuclear battery. An international nuclear operating company could provide the initial staff and training for such facilities.[5] Continued R&D, demonstrations, and institutional development would be needed to bring such a concept to fruition.[6]

Third, there are reactors where the staff has a poor safety culture and does not give safety measures the attention they require. While this category overlaps considerably with the first two, safety culture is a major problem even in wealthy developed countries that have been using nuclear power for decades. The Davis-Besse incident already mentioned, for example, arose because of a fundamental breakdown in the safety culture at the site and among regulators dealing with the site at the Nuclear Regulatory Commission, who allowed the site to postpone inspections and did not follow up on earlier indicators of a potential problem.[7] Even in the most advanced nuclear states, sustaining a strong safety culture as large numbers of new plants are built and thousands of new personnel enter the nuclear industry will pose a special challenge. China and India, with their near-term plans for rapid construction of large numbers of new reactors, will face this challenge acutely.

Operators of nuclear facilities, overseen by national regulators, are responsible for addressing such problems and ensuring nuclear safety. But the consequences of a major nuclear accident would extend far beyond national borders; the spread of that realization after Chernobyl led to the establishment of a broad international nuclear-safety regime. Today this regime includes international treaties such as the Convention on Nuclear Safety, a variety of agreements on liability in the event of a nuclear accident, a set of nonbinding international norms and standards, and a web of organizations that act to promote safety. The International Atomic Energy Agency (IAEA) has developed a series of safety standards and guides that do not carry the force of international law but are nonetheless widely followed. The World Association of Nuclear Operators (WANO), an industry organization that includes the operators of all the world's nuclear power reactors among its members, provides for exchanges of information on safety incidents, lessons learned, and best safety practices, and organizes international peer reviews of safety arrangements at member reactors. An IAEA program also offers peer reviews of safety arrangements at individual reactors, along with other programs that offer reviews of regulatory practices and other matters. The IAEA and the OECD's Nuclear Energy Agency manage a global safety incident-reporting system. There are also bilateral and multilateral nuclear safety assistance programs, international professional associations and conferences, and other groups focused on nuclear safety.[8]

This international regime has helped to achieve major improvements in nuclear safety over the more than two decades since the Chernobyl accident, but substantial gaps in the regime remain. The Convention on Nuclear Safety sets no binding standards for how safe nuclear facilities should be.[9] The IAEA peer reviews occur only when a state asks for one, and most of the world's nuclear power reactors have never had such a review. Hence, when asked the question "which reactors in the world pose the highest accident risks?" the IAEA has no real way of knowing the answer (though it can make some educated guesses). WANO peer reviews are closer to being universal, but they are far less rigorous than, for example, those of WANO's U.S. affiliate, the Institute of Nuclear Power Operations, and WANO promises its members that the results of these reviews will be kept confidential. If a WANO team finds a significant problem, WANO typically does not even tell the national regulator, unless the facility's operator agrees to do so. WANO officials have warned that some operators are not implementing all the recommendations of the peer reviews, so the same problems sometimes crop up on the next review.[10] Both WANO and the IAEA have warned that some safety incidents are not being reported, and some operators are not learning the lessons from incidents elsewhere, so that the same kinds of problems continue to occur.[11]

In 2008, an international commission convened by the IAEA recommended that (a) the IAEA should lead efforts to establish a "a global nuclear safety network" that would strengthen exchanges of safety-critical knowledge, experience, and lessons learned; (b) over time, "states should enter into binding agreements to adhere to effective global safety and standards and to be subject to international nuclear safety peer reviews"; (c) the IAEA and relevant states should greatly strengthen their efforts to help newcomer states "develop sound safety infrastructures"; and (d) the IAEA should expand its efforts to help states around the world assess and strengthen nuclear safety culture.[12] The commission argued that the IAEA's budget for nuclear-safety activities should be substantially increased to support this larger role.

STRENGTHENING SECURITY

Nuclear security requires even more urgent action. Terrorists are actively seeking nuclear weapons and the materials and expertise needed to make them, and have seriously considered sabotaging nuclear power plants.[13] The growth and spread of nuclear energy—and potentially thousands of lives and billions of dollars—will depend on the world's ability to prevent either of these threats from materializing. Achieving that goal will require major improvements in nuclear-security practices in many countries around the world.

A potential nuclear revival has quite different implications for these two threats. More nuclear reactors in more places need not increase the chance that terrorists could get their hands on the material for a nuclear bomb. Today, most nuclear power reactors run on low-enriched uranium fuel that cannot be used in a nuclear bomb without further enrichment, which is beyond plausible terrorist capabilities. These reactors produce plutonium in their spent fuel, but that plutonium is 1 percent by weight in massive, intensely radioactive spent-fuel assemblies that would be extraordinarily difficult for terrorists to steal and process into material that could be used in a bomb. If this plutonium is separated from the spent fuel by reprocessing, fabricated into new fuel, and shipped from place to place, that could increase the risk that terrorists could seize the material for a nuclear bomb unless operators take extraordinary security measures throughout the process. Fortunately, economics and counter-terrorism point in the same direction in this case: because reprocessing is much more expensive than simply storing spent fuel pending disposal, few countries that do not already reprocess their fuel are interested in starting, and some of the existing plants are running far below capacity or heading for shut down.

Nevertheless, many more nuclear power reactors in many more countries would mean more potential targets for terrorist sabotage—and more chances that some reactor's security would be weak enough that an attack would succeed in overwhelming built-in protections designed to reduce the risk of catastrophic dispersal of the reactor's radioactive core. A successful sabotage would be a catastrophe for the country where it occurred, and for its downwind neighbors. But the location of the reactor would determine the location of the damage; unlike readily transported nuclear weapons or materials, a successful attack on a reactor would not threaten lives in countries thousands of kilometers away.

Unfortunately, in many countries, the security measures in place to prevent theft of weapons-usable materials are demonstrably insufficient to defeat the kinds of threats terrorists and criminals have shown they can pose. As a result, theft and illicit trafficking of nuclear materials is not a hypothetical concern but an ongoing and current reality. The IAEA, for example, has documented 18 cases of theft or loss of plutonium or highly enriched uranium (HEU)—the essential ingredients of nuclear weapons—confirmed by the states concerned.[14] That reality was driven home in November 2007, when two armed teams simultaneously attacked the Pelindaba nuclear facility in South Africa, which contains hundreds of kilograms of HEU. One of the groups successfully disabled the security systems and the attackers made their way to the control room, shooting a security officer there before any alarm was sounded. Although they did not seize any HEU, they escaped before external security reinforcements arrived and were never apprehended.[15]

Given incidents such as these and the major improvements in nuclear safety in recent years, the probability of a catastrophic release caused by malevolent human action—a successful sabotage or a terrorist nuclear bomb—may well be higher than the chance of such a release occurring purely by accident. If so, a radical change in nuclear security practices, culture, and regulation around the world is needed, for the emphasis in the industry today focuses overwhelmingly on safety and far less on security.

As with safety, national authorities and facility operators themselves bear primary responsibility for providing effective security for nuclear weapons, weapons-usable materials, and facilities that might be vulnerable to a catastrophic sabotage.

But the international community—including the global nuclear industry—has an overwhelming stake in ensuring that they carry out this responsibility effectively. Unfortunately, international institutions for nuclear security are substantially weaker than those for nuclear safety. Because the world has yet to witness a successful act of nuclear terrorism, complacency is widespread; many policy-makers and nuclear managers around the world dismiss the danger or assume that existing security measures are more than sufficient. Most countries view nuclear security as an exclusively national responsibility, and shroud their practices in secrecy to avoid having potential adversaries learn about the kinds of defenses they might have to overcome.

The international conventions related to nuclear security, including the Convention on the Physical Protection of Nuclear Material and Facilities and the International Convention on the Suppression of Acts of Nuclear Terrorism, do not set specific standards for how secure nuclear materials or facilities should be, and include no mechanisms for verifying that states are complying with their commitments. U.N. Security Council Resolution 1540 legally obligates all U.N. member states to provide "appropriate effective" security and to account for any nuclear weapons or related materials they may have, but no one has defined what key elements are required for a nuclear security and accounting system to be considered "appropriate" and "effective."[16] The IAEA has published physical protection recommendations, but these are still vague; in the case of a substantial stock of plutonium or HEU, for example, they call for having a fence with intrusion detectors but say nothing about how difficult it should be to get past the fence or avoid setting off the detectors. As in the case of safety, IAEA-led peer reviews of security are entirely voluntary; much less than half of the world's nuclear power reactors, and very few of the sites with HEU or plutonium, have ever had an international review of their security arrangements.

The Nunn-Lugar Cooperative Threat Reduction program and similar bilateral and multilateral cooperation programs have played a crucial role in improving nuclear security over the past 15 years, particularly in the former Soviet Union. The United States has invested billions of dollars in programs designed to help countries install and operate improved security and accounting systems, and to remove weapons-usable nuclear material entirely from a wide range of sites—for example, by converting research reactors to use low-enriched uranium rather than HEU. As a result of these efforts, nuclear security at scores of sites around the world has been markedly improved, and dozens of additional sites no longer have any weapons-usable nuclear material that could be stolen.[17] But there are still many important vulnerabilities to be addressed, and these international cooperative programs have so far not focused in depth on addressing the danger of sabotage.

The world needs a fast-paced global campaign to strengthen nuclear-security measures for all the sites and transports that handle nuclear weapons or weapons-usable material, or that could result in a catastrophic release of radioactive material if sabotaged. Plutonium and HEU that might be stolen reside not only in the stockpiles of states with nuclear weapons, but also in civilian facilities that reprocess and fabricate plutonium and in research facilities that use HEU in dozens of countries around the world. President Obama has pledged to lead "a new international effort to secure all vulnerable nuclear material around the world within four years."[18] Achieving that objective will take sustained high-level leadership, an effective and comprehensive plan, broad international cooperation, and adequate resources. The job will require convincing political leaders around the world that nuclear terrorism is a real and urgent threat to *their* countries' security, worthy of increased investment of their time and resources, not just a figment of overheated American imaginations.

As part of such a global campaign, a major effort is needed to reduce dramatically the number of buildings and bunkers where nuclear weapons and the materials needed to make them exist. States must also agree on and implement effective global standards for nuclear security, not only to prevent theft of nuclear weapons or materials, but also the sabotage of nuclear reactors, so that all are providing comparable levels of security against threats that terrorists have shown they can pose. Finally, to sustain nuclear security over the long run, those responsible for providing security at individual nuclear facilities must foster a strong security culture in the workplace.[19]

In this volume, Roger Howsley describes a new institution, WINS, which may play a key role in this effort. By providing a forum were nuclear security operators can exchange best practices and ways to resolve common issues, WINS has the potential to help strengthen nuclear security worldwide and to build up security culture, convincing operators and staff that the threats are real and can be addressed effectively without breaking the bank.

DEALING WITH NUCLEAR WASTES

As reliance on nuclear power increases, so too will the problem of how to deal with highly radioactive nuclear wastes. Nuclear waste is expensive to process or dispose of underground, politically unpopular to site, potentially vulnerable to sabotage when left in overfilled pools at reactor sites, and contains plutonium that could be reprocessed for use in nuclear weapons. Fortunately, the technology of concrete and metal dry-storage casks offers a cheap, safe, and proven means to store spent nuclear fuel for decades while more permanent solutions are developed. But the politics of waste storage and disposal remains a major problem, as President Obama's recent decision to cancel the Yucca Mountain nuclear-waste repository, in the face of pressure from Senate Majority Leader Harry Reid of Nevada, makes clear. Here, too, institutions will be critical in building trust and public support for effective nuclear-waste management approaches.[20] As Charles McCombie writes in this issue, programs in which supplier states would "lease" fuel, taking back the spent fuel after it was used, and regional repositories could provide a critical means for small states to make use of nuclear energy without having to establish their own nuclear-waste repositories—and without leaving plutonium-bearing spent fuel scattered permanently in dozens of countries all over the world. "Shared disposal facilities for the spent fuel and highly radioactive wastes at the back end of the fuel cycle," writes McCombie, "should be one key component in a secure global [nuclear energy] system."

REDUCING PROLIFERATION RISKS

There is also much to be done to ensure that the growth and spread of nuclear energy will not contribute to the proliferation of nuclear weapons. Preventing proliferation is another key to large-scale nuclear energy growth. The proliferation risks posed by nuclear reactors themselves are not zero—ordinary power reactors produce plutonium in their spent fuel and require large staffs of trained people who might later be turned to a nuclear weapons program, and substantial nuclear bureaucracies that may advocate for a weapons program. But the biggest risks come not from nuclear reactors but from the materials needed to make a nuclear bomb, plutonium separated from spent fuel or highly enriched uranium, and from the uranium enrichment and plutonium reprocessing facilities that could be used to make these potential bomb materials. A world of many more nuclear reactors will require more uranium enrichment or more plutonium recycling, potentially creating more challenges to safeguarding these materials, more companies working on enrichment technologies that might leak onto the nuclear black market, or more countries with facilities that could readily be turned to producing nuclear bomb material.

Moreover, the nonproliferation regime has suffered a number of major blows over the past several years. With North Korea becoming the first state to withdraw from the Nuclear Non-Proliferation Treaty (NPT) and test a nuclear bomb, Iran apparently seeking to come up to the edge of a nuclear weapons capability while staying within the regime, and the A.Q. Khan network peddling dangerous nuclear technologies across the globe, the need for action to strengthen the global effort to stem the spread of nuclear weapons has never been clearer. And nations aspiring to produce nuclear energy are not the only states that must renew their commitment to uphold the basic rules and principles of the nonproliferation regime. To gain international support for strengthened nonproliferation measures, the nuclear weapon states will have to be seen to be living up to their end of the nonproliferation bargain as well by pursuing nuclear arms reduction and disarmament in good faith.

Many steps will have to be taken to limit proliferation risks. Iran and North Korea present the first and most urgent challenges. The outcome of today's efforts to walk North Korea back from the nuclear brink and to persuade Iran to accept restraints on its fuel-cycle activities will have a major effect on whether nuclear energy will spread peacefully or will become a hedge behind which nuclear newcomers develop the necessary infrastructure to eventually build weapons. The United States and the other partners in relevant talks must engage directly with North Korea and Iran, with packages of promised benefits and punishments large enough and credible enough to convince these states that it is in their interest to give up their nuclear weapon ambitions.

Beyond those two cases, some of the most important means of limiting the risk of proliferation include phasing out the civilian use of HEU and minimizing civil plutonium reprocessing; forging new approaches to the fuel cycle that limit the spread of nationally controlled uranium enrichment and plutonium reprocessing facilities; building new approaches to police, intelligence, and export control cooperation to stop black-market transactions in nuclear technology; strengthening international safeguards; and strengthening enforcement when states violate their nonproliferation obligations.

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One approach that holds special promise as a nonproliferation tool is the proposed IAEA-sponsored fuel bank, which is described by Tariq Rauf and Zoryana Vovchok in this issue. The idea is to provide a nonpolitical, nondiscriminatory mechanism for supplying nuclear fuel to any state that is in compliance with its nuclear-safeguard obligations. Having an assured backup if fuel supplies were ever cut off could strengthen states' incentives not to bother with the major investment required to build their own uranium enrichment facilities, thus limiting the long-term proliferation risks posed by such facilities.[21] As most countries already have high confidence in the existing commercial market for fresh fuel, arrangements that would solve countries' spent fuel problem by allowing them to send their foreign-supplied spent fuel away—as described by Charles McCombie in this issue—could provide an even more powerful incentive for countries to rely on international fuel supply. In the future, as outgoing director-general of the IAEA, Mohammed ElBaradei, has argued, the goal should be a shift toward international or multinational control of all enrichment and reprocessing—perhaps starting with new facilities and eventually converting existing plants to some form of multinational ownership and control—"so that no one country has the exclusive capability to produce the material for nuclear weapons."[22]

New technologies and approaches to their use could raise significant future barriers to proliferation. Some of the small "nuclear battery" reactor concepts mentioned earlier, for example, are being designed to reduce proliferation risks through a combination of technological innovation (such as sealed reactor cores with no on-site access to the fuel) and new institutional arrangements (such as international firms to build, operate, and remove such reactors).[23] These concepts are still in development, however, and it remains to be seen whether the promise of real systems will match that envisioned while the reactors are still on paper. In particular, cost may be a major issue for these designs: the nuclear reactors on sale today are predominantly in the 1-1.6 gigawatt-electric (GWe) class because of economies of scale, and it remains to be seen whether very small reactors can make up in economies of production scale what they lose in economies of physical scale.

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But for decades to come, it will be institutional rather than technological innovations that contribute the most to stemming the spread of nuclear weapons.[24] The foundation of all the nonproliferation institutions is the Nuclear Non-Proliferation Treaty; all states except India, Pakistan, Israel, and North Korea are now parties. The NPT and the global nonproliferation regime have been largely unheralded success stories. There has been no net increase in the number of states with nuclear weapons in 20 years (South Africa dropped off the list, becoming the first case of real nuclear disarmament, and North Korea added itself to the list), an astonishing achievement, given that this 20 years included the chaos following the collapse of the Soviet Union, the operation of the A.Q. Khan network in its exporting phase, and secret nuclear weapons programs in Iraq, Libya, Syria, Iran, and North Korea. There are now more states that have started nuclear weapons programs and verifiably abandoned them than there are states with nuclear weapons—meaning that nonproliferation efforts succeed more often than they fail, even when states have already started down the nuclear-weapons road. But given the new pressures the regime now faces, even stronger nonproliferation agreements and institutions are needed to ensure continued success.

The IAEA is the primary international organization charged with overseeing compliance with nonproliferation rules. Its safeguards agreements with member states, for example, play a critical role in ensuring that the use of nuclear technology in states without nuclear weapons remains peaceful. But IAEA safeguards have important weaknesses, particularly in the difficult job of detecting undeclared activities at covert sites. The IAEA faces significant constraints in its access to sites, information, resources, technology, and the Security Council. There are also important issues of institutional culture that require constant attention; for example, balancing the need to maintain positive relationships with states—which is essential for the IAEA to do be able to do its work—with an appropriate investigatory attitude is a continuous challenge.

With respect to access to sites and information, the "Additional Protocol" to safeguards agreements, negotiated in the 1990s in response to the post-1991 revelation of the full extent of Iraq's nuclear activities, is a major advance. For those states that agree to it, the Additional Protocol requires states to disclose more information on nuclear-related activities, permits the IAEA access to an expanded set of sites, allows for short-notice inspections, and is intended to provide at least limited confidence not only that a state is not diverting nuclear material from declared nuclear facilities, but also that the state does not have secret, undeclared nuclear-related activities. However, many issues remain. First, there are dozens of states, some with significant nuclear activities, that have not acceded to the Additional Protocol more than a decade after its adoption. Second, the Additional Protocol still focuses the IAEA's authority on sites involving nuclear material or the technologies to make such materials. When the IAEA wanted to visit, for example, Parchin in Iran, to investigate accusations that explosive experiments related to nuclear weapons might have taken place, there were no undisputed legal grounds for doing so.[25] To address some of these issues, former IAEA deputy director-general for safeguards, Pierre Goldschmidt, has suggested that the U.N. Security Council should pass a legally binding resolution that would impose a wide range of additional safeguards obligations on any state found to be in violation of its safeguards agreements, including broad-ranging inspections and a right for international inspectors to interview key scientists and other participants in nuclear programs in private.[26]

With respect to resources, the IAEA's budget for implementing nuclear safeguards worldwide is roughly the size of the budget of the Vienna police department, a situation that clearly has limited what the IAEA can hope to do, even as the demand for safeguards inspections is increasing. Unfortunately, the IAEA has been caught up in the broader politics of efforts to reform the U.N. system and restrain the growth of the budgets of U.N. agencies. At the same time, with the nuclear revival increasing demand for nuclear experts in the private sector and IAEA salaries and other personnel policies constrained by participation in the common personnel system for all U.N. agencies, the IAEA has had increasing difficulty recruiting and retaining the nuclear experts it needs to carry out its mission. Roughly half of all senior IAEA inspectors and managers will reach the agency's mandatory retirement age within five years.[27]

The IAEA and various of its member states are exploring a variety of new technologies that can contribute to the safeguards mission, from ever-evolving techniques for analyzing tiny particles taken in swipes from nuclear facilities to systems for monitoring the flow of nuclear materials in sensitive facilities in real time. Finding hidden nuclear facilities remains a fundamental challenge, however. Centrifuge enrichment plants, in particular, are small and potentially easy to hide; a facility capable of producing enough material for a nuclear bomb every year might not use any more power or cover any more area than a typical supermarket. And, in some cases, the safeguards challenge is not just to develop the technology but also to get industry to permit its use. The enrichment industry, for example, has so far refused to allow the IAEA to use equipment for continuous monitoring of the flow in their plants.

Finally, there is the question of the will and effectiveness of the U.N. Security Council in requiring states to comply with IAEA inspections, and in enforcing nonproliferation obligations more generally. When North Korea was found to be in violation of its safeguards obligations in the mid-1990s, the Security Council issued a statement but did nothing more. Meanwhile, the United States reached an accord with North Korea that postponed IAEA special inspections many years into the future. More recently, in the case of Iran, the U.N. Security Council passed legally binding resolutions requiring Iran to comply with IAEA inspection requirements, provide additional transparency to resolve key issues, and suspend its enrichment and reprocessing activities. Iran has ignored these resolutions, leading the Security Council to impose a series of mild sanctions against Iran that have not caused that country to change course.

In 2008, an international commission on the future of the IAEA called on states "to give the IAEA access to additional information, sites, and people, along with the money, qualified personnel, and technology that it needs to carry out its mission." The commission made a wide range of more specific recommendations, from universal adoption of the Additional Protocol to interpreting the agency's existing authority to give it the responsibility to "inspect for indicators of nuclear weaponization activities."[28]

The Nuclear Suppliers Group (NSG) is also an important international nonproliferation institution, but it faces ongoing challenges to its effectiveness and legitimacy. Established in response to the 1974 Indian nuclear test, the NSG has traditionally operated by consensus and, as more and more states have joined, consensus on modernizing its rules has become more difficult to achieve. Most NSG participants, for example, strongly support making the Additional Protocol a condition for nuclear exports from NSG states, but Brazil (which has not accepted the Protocol) has resisted. Canada has similarly refused to agree that enrichment technologies be exported only on a "black-box" basis, i.e., without the recipient being able to have access to the technology.[29] Turkey recently objected to a proposal that would allow exporting states to consider proliferation problems in a recipient's geographic region when deciding whether to approve an export.[30] NSG members have held several rounds of discussions on strengthening export guidelines, but such objections have so far stalled these efforts. Some key states that may be worrisome sources of nuclear technology—including Pakistan, India, Israel, North Korea, and Iran, among others—are outside of the NSG. The NSG also has a problem of legitimacy as a self-selected group: many developing countries believe the NSG is effectively a cartel that unfairly restricts nuclear trade, and is contrary to the NPT requirement to cooperate in the peaceful uses of nuclear energy.

The past decade has seen a variety of efforts at institutional innovation in the nonproliferation regime. With the advent of the Additional Protocol, the IAEA is in the process of a fundamental shift from simply measuring the nuclear material at declared facilities to a "state-level approach" that seeks to understand all the nuclear activities of each state, and to look for hints of secret, undeclared facilities. In the aftermath of the A.Q. Khan network and the 9/11 attacks, the U.N. Security Council unanimously passed Resolution 1540, which legally requires every U.N. member state to take a wide range of actions, from establishing "appropriate effective" export controls and security for nuclear stockpiles to criminalizing any effort to help nonstate actors with nuclear, chemical, or biological weapons. Unfortunately, however, no one has yet fleshed out what specific measures are required for export control or nuclear-security systems to meet the "appropriate effective" standard, and relatively little has been done to help states put effective systems in place.

Efforts to get states to work together to prevent proliferation without new treaties or organizations may also, over time, lead to building new institutions. After an embarrassing episode in which the United States found it had no authority to stop a ship and seize its cargo on the high seas, even though it was carrying North Korean missiles to Yemen (there was no agreement preventing Yemen from making such a purchase), the Bush administration launched the Proliferation Security Initiative (PSI), a voluntary grouping of countries that agrees to stop ships or aircraft carrying illicit nuclear, chemical, biological, or missile cargo when they are flying the flag of a participating country or in one of those countries' waters or airspace.[31] While the Bush administration went out of its way to avoid institutionalizing the PSI and the later Global Initiative to Combat Nuclear Terrorism out of a misplaced allergy to international institutions, President Obama has argued that because these threats are likely to be long-lasting, both should be turned "into durable international institutions."[32]

Some innovations were less positive or less successful. In 2005, for example, President Bush reversed years of international nonproliferation policy by agreeing to supply civilian nuclear technology to India, even while India continued its nuclear weapons program. The Nuclear Suppliers Group eventually blessed this new arrangement, creating a situation in which some non-nuclear-weapon states saw India getting all the benefits they received for being a party to the NPT without joining the treaty or even capping its growing nuclear-weapons stockpile, let alone giving it up. The Bush administration also called for a major international discussion of strengthening the safeguards system, but this effort collapsed in disarray with no agreement on even the most modest new steps.[33] Similarly, the 2005 review conference for the NPT fell apart without reaching any agreements, in large part because of the Bush administration's refusal to even discuss the disarmament commitments that all parties had agreed to at the previous review.

Fortunately, with President Obama's commitment to "a world without nuclear weapons," along with renewed support for negotiating deeper near-term reductions in U.S. and Russian nuclear arms, ratifying the Comprehensive Test Ban Treaty, and negotiating a verified cutoff of the production of fissile materials for weapons, the atmosphere in international nuclear discussions has changed dramatically, greatly improving the prospects for the next NPT review in 2010.[34] Of course, the goal of zero nuclear weapons is a long-term prospect, and it is not yet certain whether it can be achieved. But it is crucial to begin taking steps in that direction, reducing the nuclear danger at each step.

Fundamentally, strengthened nonproliferation measures are critical to a safe future for nuclear power, but they will not get international support unless President Obama and the leaders of the other nuclear weapon states make good on their NPT obligation to negotiate in good faith toward nuclear disarmament. Reducing existing arsenals may not have any effect on convincing North Korea or Iran not to want nuclear weapons, but it will have a major effect on convincing other countries to vote for stronger inspections, enforcement, export controls, and the like, all of which will help cope with the challenges posed by states violating the regime. A future of expanded reliance on nuclear power necessarily implies a future of much reduced reliance on nuclear weapons.

ENABLING A SAFE, PEACEFUL, AND VIBRANT NUCLEAR FUTURE

Creating the conditions for nuclear energy to grow on the scale needed for it to be a significant part of the world's response to climate change without posing undue risks is a global challenge. New steps to ensure safety, security, waste management, nonproliferation, and progress toward disarmament will be essential to success. All of these will require close international cooperation and stronger international institutions. In particular, achieving the safe, secure, and peaceful growth of nuclear energy will require an IAEA with more money, more authority, more information, more technology, and more support from the U.N. Security Council.

With nuclear energy growth still proceeding at a modest pace and much of the industry focused on the inevitable difficulties of building the first few reactors of the new generation of designs, many policymakers have been putting off the issues addressed here for a later day. But it will take time to build the institutions needed to guide a peaceful and vibrant nuclear future. It is essential that governments act in time, before an accident or terrorist attack shows us where and how we were too late.

Endnotes

1. S. Pacala and R. Socolow, "Stabilization Wedges," *Science*, August 13, 2004, pp. 968-972.
2. Pacala and Socolow envision 700 1-gigawatt nuclear plants substituting for efficient coal plants by 2050. The existing roughly 370 gigawatt-electric (GWe) of nuclear energy will also have to be

replaced by 2050, for a total requirement to build over 1,000 1-GWe reactors in the next 40 years. Indeed, since the "business-as-usual" scenario presumably already includes a substantial amount of reactor construction, adding 700 reactors would require a still faster pace of reactor construction.

3. For a similar argument, see Commission of Eminent Persons, *Reinforcing the Global Nuclear Order for Peace and Prosperity: The Role of the IAEA to 2020 and Beyond* (Vienna: International Atomic Energy Agency, May 2008).
4. The authors are grateful to Andrew Newman for research assistance with this section.
5. See U.S. Department of State, "Nuclear Proliferation Assessment Statement: Pursuant to Section 123a. of the Atomic Energy Act of 1954, as Amended, With Respect to the Proposed Agreement for Cooperation Between the Government of the United States of America and the Government of the United Arab Emirates Concerning Peaceful Uses of Nuclear Energy" (Washington, DC: Department of State, April 2009), p. 4.
6. For a discussion of the potential nonproliferation advantages of such reactors in the context of large-scale growth and spread of nuclear energy, see Harold Feiveson, Alexander Glaser, Marvin Miller, and Lawrence Scheinman, *Can Future Nuclear Power Be Made Proliferation Resistant?* (College Park, MD: Center for International and Security Studies at Maryland, University of Maryland, July 2008); see also http://cissm.umd.edu/papers/files/future_nuclear_power.pdf (accessed June 29, 2009). For an article advocating a multinational consortium to provide and operate such reactors around the world, see Evgeniy Velikhov, Vyacheslav Kuznetsov, and Vladimir Schmelev, "Proposal for Nuclear Power Development on the Basis of Serial Medium-Capacity NPP in Non-Proliferation Conditions," paper presented at Achieving a World Free of Nuclear Weapons: International Conference on Nuclear Disarmament, Oslo, Norway, February 2008, http://disarmament.nrpa.no/wp-content/uploads/2008/02/Paper_Kuznetsov.pdf (accessed July 15, 2009).
7. See, for example, U.S. Nuclear Regulatory Commission, *NRC's Regulation of Davis-Besse Regarding Damage to the Reactor Vessel Head, Inspector General Report on Case No. 02-03S* (Washington, DC: Nuclear Regulatory Commission, December 30, 2002), http://www.nrc.gov/reading-rm/doc-collections/insp-gen/2003/02-03s.pdf (accessed June 29, 2009), and U.S. Government Accountability Office, *Nuclear Regulation: NRC Needs to More Aggressively and Comprehensively Resolve Issues Related to Davis-Besse Nuclear Plant's Shutdown*, GAO-04-415 (Washington, DC: GAO, May 2004), http://www.gao.gov/new.items/d04415.pdf (accessed June 29, 2009).
8. For an overview of nuclear safety institutions and recommendations, see International Nuclear Safety Advisory Group (INSAG), *Strengthening the Global Nuclear Safety Regime, INSAG-21* (Vienna: International Atomic Energy Agency, 2006). A useful summary of recent activities can be found in International Atomic Energy Agency, *Nuclear Safety Review for the Year 2007*, GC(52)/INF/2 (Vienna: IAEA, July 2008), http://www.iaea.org/About/Policy/GC/GC52/GC52InfDocuments/English/gc52inf-2_en.pdf (accessed July 3, 2009).
9. For an intriguing assessment of the convention and a suggestion of an alternative approach, see Jack N. Barkenbus and Charles Forsberg, "Internationalizing Nuclear Safety: the Pursuit of Collective Responsibility," *Annual Review of Energy and Environment*, vol. 20 (1995), pp. 179-212.
10. See Ann MacLachlan, "WANO Warns Safety Lapse Anywhere Could Halt 'Nuclear Renaissance,'" *Nucleonics Week*, September 27, 2007.
11. Indeed, in 2006, then-WANO managing director Luc Mampaey complained that some utilities were not reporting incidents at all, and some types of incidents were continuing to recur despite repeated WANO reports about them. Mampaey warned that safety lapses anywhere could bring a halt to the nuclear revival. See MacLachlan, "WANO Warns." Improving incident reporting and implementation of lessons learned is a major focus of INSAG, *Strengthening the Global Nuclear Safety Regime.*
12. Commission of Eminent Persons, *Reinforcing the Global Nuclear Order*.
13. For an overview of nuclear security issues focusing primarily on nuclear weapons and materials,

see Matthew Bunn, *Securing the Bomb 2008* (Cambridge, MA: Project on Managing the Atom, Harvard University), and Nuclear Threat Initiative, November 2008). For an overview of the problem of nuclear sabotage, see 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), pp. 39-64, http://books.nap.edu/openbook.php?isbn=0309084814 (accessed July 10, 2009).

14. IAEA Illicit Trafficking Database (Vienna: IAEA, September 2008), http://www.iaea.org/NewsCenter/Features/RadSources/PDF/fact_figures2007.pdf (accessed July 3, 2009). Perhaps the best summary of the available data on nuclear and radiological smuggling is "Illicit Trafficking in Radioactive Materials," in *Nuclear Black Markets: Pakistan, A.Q. Khan, and the Rise of Proliferation Networks: A Net Assessment* (London: International Institute for Strategic Studies, 2007), pp. 119-138 (Lyudmila Zaitseva, principal author).
15. See "60 Minutes: Assault on Pelindaba," *CBS News*, November 23, 2008, http://www.cbsnews.com/stories/2008/11/20/60minutes/main4621623.shtml (accessed July 15, 2009). See also Bunn, *Securing the Bomb* 2008, pp. 3-4, and sources cited therein.
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17. See Bunn, *Securing the Bomb 2008*, pp. 17-113.
18. See The White House, Office of the Press Secretary, Remarks by President Barack Obama, Prague, Czech Republic, April 5, 2009, http://www.whitehouse.gov/the_press_office/Remarks-By-President-Barack-Obama-In-Prague-As-Delivered/ (accessed June 6, 2009).
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21. For a summary of proposals for strengthening fuel assurances see "12 Proposals on the Table" *IAEA Bulletin*, vol. 49, no. 2 (March 2008), pp. 62-63, available at http://www.iaea.org/Publications/Magazines/Bulletin/Bull492/49204845963.pdf (accessed July 15, 2009). See also Erwann O. Michel-Kerjan and Debra K. Decker, "Insure to Assure: A New Paradigm for Nuclear Nonproliferation and International Security, " *Innovations: Technology, Governance, Globalization*, vol. 4, no. 2, (Spring 2009), pp. 139-155.
22. Mohamed ElBaradei, "Reviving Nuclear Disarmament," conference on "Achieving the Vision of a World Free of Nuclear Weapons, Oslo, February 26, 2008.
23. See Feiveson, Glaser, Miller, and Scheineman, *Can Future Nuclear Power Be Made Proliferation Resistant?*
24 For the most complete available listing of relevant institutions, see James Martin Center for Nonproliferation Studies, Monterey Institute of International Studies, Inventory of International Nonproliferation Regimes and Organizations, available at http://cns.miis.edu/inventory/index.htm (accessed July 6, 2009).
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26. Pierre Goldschmidt, "IAEA Safeguards: Dealing Preventively with Non-Compliance" (Washington, DC: Carnegie Endowment for International Peace and Belfer Center for Science and International Affairs, Harvard University, July 12, 2008), http://www.carnegieendowment.org/files/Goldschmidt_Dealing_Preventively_7-12-08.pdf (accessed July 6, 2009).
27. Commission of Eminent Persons, *Reinforcing the Global Nuclear Order*, pp. 29-31.
28. Commission of Eminent Persons, *Reinforcing the Global Nuclear Order*, pp. 18-20.
29. Daniel Horner, "NSG Mulling New Text on Criteria for Sensitive Nuclear Exports" *Nuclear Fuel*,

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32. The White House, "Remarks by President Barack Obama," *op. cit.*
33. See, for example, Mark Hibbs, "Board Sinks IAEA Safeguards Panel with No Agreement on Improvements," *Nuclear Fuel*, July 2, 2007.
34. For Obama's statement, see The White House, "Remarks by President Barack Obama," *op. cit.*