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Balancing risks: nuclear energy & climate change

Four convictions motivate this paper.¹ First, *nuclear power could make a significant contribution to climate change mitigation*. To do so, however, nuclear power would have to be deployed extensively, including in the developing world. A “one-tier” world will be required – that is, a world with an agreed set of rules to govern nuclear power that are the same in all countries.

Second, *the world is not now safe for a rapid global expansion of nuclear energy*. Nuclear-energy use today relies on technologies and a system of national governance of the nuclear fuel cycle that carry substantial risks of nuclear weapons proliferation. There are still more than 20,000 nuclear weapons in the world, and in the current international system, nations see these weapons as instruments of power and sources of prestige. These nations have competing interests and long-standing conflicts. There are also subnational groups that resort to force. The risks that a global expansion of nuclear power will facilitate nuclear proliferation and incidents of nuclear terrorism, or even lead to regional nuclear war, are significant. Nuclear war is a terrible

trade for slowing the pace of climate change.

Third, *a world considerably safer for nuclear power could emerge as a co-benefit of the nuclear disarmament process*. The national-security community is currently engaged, to an unprecedented degree, in seeking progress toward nuclear disarmament. A by-product of this process could be different technology choices and innovations in the governance of nuclear power – notably, a halt to spent-fuel reprocessing to separate plutonium as well as multinational ownership and control of uranium enrichment facilities. These developments could begin to decouple nuclear power from nuclear weapons.

Finally, *the next decade is critical*. While several approaches to climate change mitigation are available for immediate, rapid scale-up, nuclear power could be so in maybe 10 years, provided the coming decade is used to establish adequate technologies and new norms of governance. Nuclear power ought to be deployed seriously as a mitigation strategy only when and if it can provide a sustainable contribution. The world will not benefit if nuclear power’s contribution is withdrawn a decade or two after global scale-up begins, as a result of flaws related to its coupling to nuclear weapons.

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There are 3,000 billion tons of carbon dioxide (CO₂) in the atmosphere today, about 800 billion tons more than there were 200 years ago. For centuries further back, the amount of CO₂ in the atmosphere was about constant: the forests and oceans and atmosphere were in approximate equilibrium. Disequilibrium is increasing with every passing year, as human beings bring carbon from deep under ground to the surface (in fossil fuel) and burn it.

The climate science and policy communities have positioned warning lights between 3,500 and 4,000 billion tons of CO₂, levels that would be reached in 30 and 60 years, respectively, at today's rate of growth. For such CO₂ levels, although the most favorable outcomes could be benign, the worst outcomes could be catastrophic for human civilization, which has built many of its cities on coasts and has matched its choices of crops to relatively predictable snowmelt, rainfall, and temperature patterns. We are confronted with a risk-management problem of unprecedented complexity.

Everything about climate change is global. The global atmosphere is well stirred and scarcely registers where CO₂ is emitted. Demand for electricity and fuels is driven by middle-class consumption, which takes similar forms in countries with a wide range of per capita CO₂ emissions.² Electricity serving air conditioner compressors, computer circuits, incandescent lights, and appliances arrives along wires that, worldwide, run from power plants of only a few kinds. To be sure, nations differ in their endowments of resources; but, even so, a good strategy for mitigating climate change in one country will be a good strategy in many other countries.

A "wedge model," published in 2004, quantifies the task of global climate

change mitigation.³ We human beings today emit 30 billion tons of CO₂ per year by burning fossil fuels. We would emit 60 billion tons per year in 2050 if we were oblivious to climate change (the so-called business-as-usual world), and we can congratulate ourselves if we cut the anticipated 2050 emissions rate in half, emitting CO₂ at the same rate in 2050 as today. A *stabilization wedge* is a campaign or strategy motivated by climate change (that is, not happening for other reasons) that results in 4 billion tons of CO₂ per year not emitted in 2050.

Available options for wedges include energy efficiency wedges, wind wedges, nuclear wedges, and wedges from CO₂ capture and storage (CCS) – capturing the CO₂ produced at coal plants and burying it deep below ground. About eight wedges are needed to pat ourselves on the back, and we can choose a portfolio of them in many ways. A portfolio of wedges is needed because solving climate change with only one or two kinds of wedges is close to impossible. Moreover, there are enough options for the portfolio that none is indispensable. Thus, climate change mitigation can succeed without nuclear power, or any other single option, at some increased overall cost for mitigation.⁴

A nuclear wedge is equivalent to 700 large base load nuclear power plants on the scene in 2050 and 700 equally large base load coal plants not built.⁵ The world has the equivalent of about 350 large nuclear plants today, so phasing out nuclear power in favor of coal power is minus half a wedge.

Arguments for giving priority to climate change mitigation are uncomfortable bedfellows with arguments for nuclear power. The dissonance arises among a political constituency, particularly powerful in Europe, for which mitigating climate change is seen as an op-

portunity for pursuing deep changes in social and economic structures and in values – away from consumerism and centralized authority. To meet this aspiration, climate policy often promotes wind power, solar thermal and solar photoelectric power, and other forms of renewables, relative to nuclear energy. This perspective also underpins the climate-policy focus on energy efficiency as a way to reduce global energy demand.

On the other hand, putting a price on CO₂ emissions as a way to mitigate climate change helps nuclear power. Roughly, an emissions price of \$20 per ton of CO₂ gives nuclear power a 2¢/kWh boost relative to power from coal and a 1¢/kWh boost relative to power from natural gas – in both cases assuming that these fossil fuel plants vent rather than capture and store CO₂.⁶ Moreover, serious CO₂ management may be accompanied by support for accelerated electrification of the economy to reduce dispersed emissions from transportation and space heating, which would increase overall demand for electric power.

In this paper we consider a nuclear future where 1,500 GW of base load nuclear power is deployed in 2050. A nuclear fleet of this size would contribute about one wedge, if the power plant that would have been built instead of the nuclear plant has the average CO₂ emissions per kilowatt hour of all operating plants, which might be half of the value for a coal plant.⁷ Base load power of 1,500 GW would contribute one fourth of total electric power in a business-as-usual world that produced 50,000 terawatt-hours (TWh) of electricity per year, two-and-a-half times the global power consumption today.⁸ However, in a world focused on climate change mitigation, one would

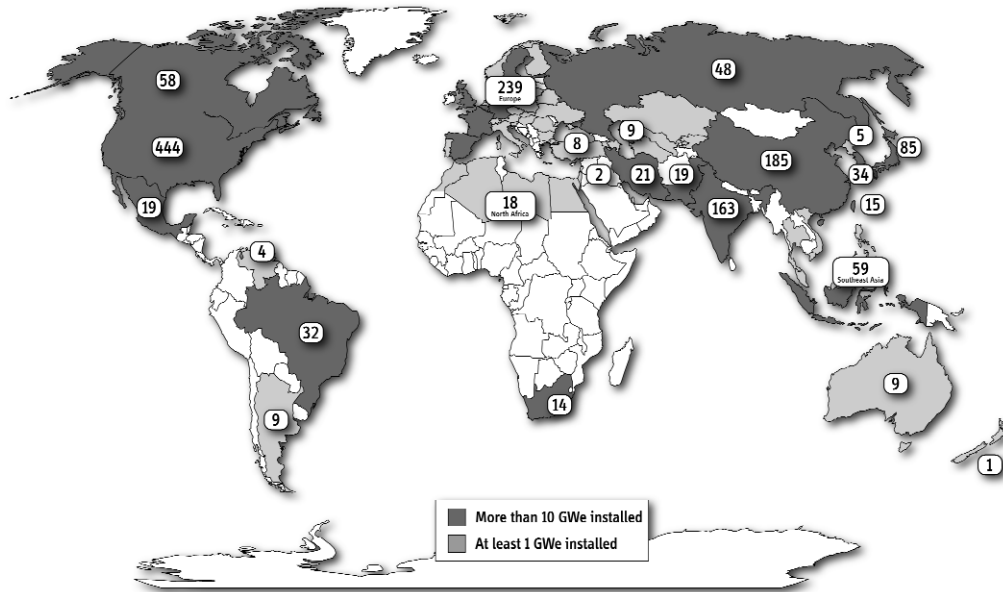
expect massive global investments in energy efficiency – more efficient motors, compressors, lighting, and circuit boards – that by 2050 could cut total electricity demand in half, relative to business as usual. In such a world, 1,500 GW of nuclear power would provide half of the power.

We can get a feel for the geopolitical dimension of climate-change mitigation from the widely cited scenarios by the International Energy Agency (IEA) presented annually in its *World Energy Outlook (WEO)*,⁹ even though these now go only to 2030. The *WEO 2008* estimates energy, electricity, and CO₂ emissions by region. Its 2030 world emits 40.5 billion tons of CO₂, 45 percent from electric power plants. The countries of the Organisation for Economic Co-operation and Development (OECD) emit less than one third of total global fossil fuel emissions and less than one third of global emissions from electric power production. By extrapolation, at mid-century the OECD could contribute only one quarter of the world's greenhouse gas emissions.

It is hard for Western analysts to grasp the importance of these numbers. The focus of climate change mitigation today is on leadership from the OECD countries, which are wealthier and more risk averse. But within a decade, the targets under discussion today can be within reach only if mitigation is in full gear in those parts of the developing world that share production and consumption patterns with the industrialized world.

The map (see Figure 1) shows a hypothetical global distribution of nuclear power in the year 2050 based on a high-nuclear scenario proposed in a widely cited MIT report published in 2003.¹⁰ Three-fifths of the nuclear capacity in 2050 as stated in the MIT report is locat-

Figure 1
The Geography of a Hypothetical Nuclear Expansion to 1,500 GWe



In this scenario, 58 countries would be using nuclear energy, but only about 40 percent of the capacity would be in non-OECD countries. Source: Based on information from *The Future of Nuclear Power* (MIT, 2003).

ed in the OECD, and more nuclear power is deployed in the United States in 2050 than in the whole world today. The worldview underlying these results is pessimistic about electricity growth rates for key developing countries, relative to many other sources. Notably, per capita electricity consumption in almost every developing country remains below 4,000 kWh per year in 2050, which is one-fifth of the assumed U.S. value for the same year. Such a ratio would startle many analysts today – certainly many in China.

It is well within limits of credulity that nuclear power in 2050 could be nearly absent from the United States and the European Union and at the same time widely deployed in several of the countries rapidly industrializing today. Such a bifurcation could emerge, for example, if public opposition to nu-

clear power in the United States and Europe remains powerful enough to prevent nuclear expansion, while elsewhere, perhaps where modernization and geopolitical considerations trump other concerns, nuclear power proceeds vigorously. It may be that the United States and other countries of the OECD will have substantial leverage over the development of nuclear power for only a decade or so.

Change will not happen overnight. Since 2006, almost 50 countries that today have no nuclear power plants have approached the International Atomic Energy Agency (IAEA) for assistance, and many of them have announced plans to build one or more reactors by 2020. Most of these countries, however, are not currently in a good position to do so. Many face important technical and economic con-

straints, such as grid capacity, electricity demand, or GDP. Many have too few trained nuclear scientists and engineers, or lack an adequate regulatory framework and related legislation, or have not yet had a public debate about the rationale for the project. Overall, the IAEA has estimated that “for a State with little developed technical base the implementation of the first [nuclear power plant] would, on average, take about 15 years.”¹¹ This lead time constrains rapid expansion of nuclear energy today.

A wedge of nuclear power is, necessarily, nuclear power deployed widely – including in regions that are politically unstable today. If nuclear power is sufficiently unattractive in such a deployment scenario, nuclear power is not on the list of solutions to climate change.

Nuclear power is not just another wedge. Briefly, here are some of the many distinctive attributes of nuclear power:

- *Time-tested.* Relative to competing wedges like renewable energy and CCS, nuclear power has been in place longer. Commercial nuclear power has been deployed for about 50 years and today is found in 30 countries. Deployment is highly concentrated, however; 10 countries operate more than 80 percent of all power reactors.
- *Small physical flows.* The thermal energy required to produce 1,000 MW of power for a year is released from the fission of only 1 ton of uranium in fuel produced from 200 tons of uranium, but from the burning of 3 million tons of coal. The flip side of compactness, of course, is that danger comes in very small packages: it takes only a few kilograms of fissile material to make a nuclear weapon.
- *Minimal CO₂ emissions.* About 90 percent of the CO₂ is expected to be excluded from the atmosphere if coal power and gas power are combined with CO₂ capture and storage. (The economic optimum percent, to be sure, depends on the CO₂ emissions price.) In that case, the CO₂ emissions from CCS power, nuclear power, and most forms of renewable energy are likely to be comparably small – all emitting less than 100 grams of CO₂/kWh, one-tenth of the value for today’s coal plants.
- *Large, centralized plants with fixed output.* To be economic, nuclear plants are large and connected to extensive electricity grids that distribute power over long distances. The power output of nuclear power plants is not easily ramped up and down, rendering it an inflexible component of an electric power system. The inflexibility of base load nuclear power and the intermittency of wind and solar energy share the feature that neither of these low-CO₂ emitters can meet a time-varying demand for electric power without assistance from complementary systems: load-following and peaking plants and storage.
- *Safety makes all plants mutual hostages.* The Three Mile Island and Chernobyl accidents of 1979 and 1986, respectively, taught the world that a nuclear power accident anywhere in the world affects the prospects for nuclear power everywhere. Nuclear energy is more “brittle” than other strategies to mitigate climate change, as one major future accident could overnight nullify the resources and time invested in nuclear power made up to that point.
- *Nuclear power plants are potential military targets.* It is all too likely that a commercial nuclear power plant in a country at war would be attacked, with horrendous

dous consequences. No taboo on such attacks exists today.¹²

- *Storage of spent fuel remains a problem.* At the advent of nuclear power, its advocates promised that no future generation would need to attend to our wastes. That goal of early final disposal has proven to be overly ambitious. Today, the second best approach to the waste problem is interim dry-cask storage of nuclear spent fuel, now widely deployed, which provides a century-scale solution while the search for solutions that isolate nuclear wastes for millennia continues.
- *Coupling to nuclear weapons.* With a nuclear power plant comes a fuel cycle, with a front-end that can require uranium isotope enrichment and a back-end that can entail the separation of plutonium and its insertion into commerce. Both the front- and back-end present significant and enduring challenges.

For the rest of this paper, we focus only on the last of these aspects of nuclear power. In our view, the fact that nuclear power is coupled to nuclear weapons is the most disabling attribute of global nuclear power at the present time.

Separated plutonium and highly enriched uranium are the key ingredients for making nuclear weapons. It is widely accepted that the production or acquisition of these fissile materials is the most difficult, visible, and time-consuming step in the proliferation process. Reprocessing and enrichment under national control essentially removes this obstacle and offers – intended or not – important latent proliferation capabilities.

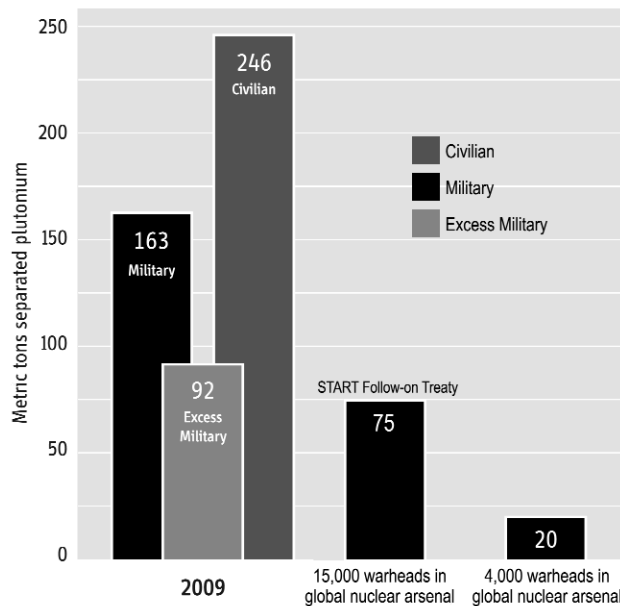
Regarding reprocessing and plutonium cycle, the world is now divided. Six countries reprocess their commer-

cial spent fuel today. France, India, Japan, and Russia are deeply committed to reprocessing; China operates a pilot reprocessing plant and is contemplating commercial reprocessing today; and the United Kingdom is on the verge of abandoning reprocessing. The United States does not reprocess civilian spent fuel nor does it introduce plutonium into its power plants, policies established under Presidents Ford and Carter.

The principal arguments against plutonium recycling are that separation, stockpiling, transport, and use of plutonium create risks of diversion to military purposes and risks of theft, the latter being of particular concern in the context of efforts to prevent nuclear terrorism. Compared to other types of nuclear facilities, reprocessing plants are extremely difficult and costly to safeguard.

The bar graph (see Figure 2) shows the quantities of separated plutonium in the world today. Civilian-separated plutonium and military-separated plutonium are both roughly equal at about 250 tons.¹³ Military plutonium is in two categories: material in the weapons complex and material declared “excess” as a result of reductions from previous warhead levels. The bar graph also shows the substantial further reductions in military plutonium associated with nuclear weapons if the world’s weapons stockpile is reduced first to 15,000 and then 4,000 warheads.¹⁴ In this process, additional military stocks would become excess and would need to be disposed of. Over time, unless reprocessing of civilian spent fuel swiftly draws to a close, the world can expect to become increasingly preoccupied with latent proliferation and “break-out”¹⁵ associated with civilian-separated plutonium – even if nuclear power does not expand significantly. A global nuclear power expansion

Figure 2
Military- and Civilian-Separated Plutonium Today, and Military
Plutonium in Weapons in a Disarming World



We assume an average of 4 kg of plutonium per warhead and a working stock of 20 percent. Civilian stockpiles are based on the latest declarations for the beginning of 2008. The current military stockpile carries an error bar of plus or minus 25 tons, largely because of the uncertainties in the estimate of Russia's inventory. Figure based on information from International Panel on Fissile Materials, *Global Fissile Material Report 2009* (Princeton, N.J.: IPFM, forthcoming).

with reprocessing makes matters much worse.

So far, no country that decided to pursue commercial reprocessing has managed to balance the rates of separation and use of plutonium, which has led to a continuous increase of civilian plutonium inventories over the past decades – hypothetically enough for more than 30,000 weapons.¹⁶ The flow of plutonium could be enormous in a world with much more nuclear energy. The 2003 MIT report works out the plutonium flows for a scenario with 1,500 GW of nuclear power where 40 percent of total capacity is from breeder reactors.¹⁷

About 1,000 tons of plutonium would be separated from the spent fuel each year to fabricate new fuel for these reactors. The IAEA cannot reduce the overall uncertainty of measurements for the annual material balance in reprocessing plants much below 1 percent.¹⁸ Assuming that 20 large-scale reprocessing plants existed in this world, the uncertainty would be equivalent to 500 kg of plutonium every year for every plant – enough for 60 bombs per year from each of these plants. Within these margins, the IAEA would be unable to confirm with high confidence that all material is accounted for. It is hard to see

how these flows and levels of uncertainty could ever be acceptable, in particular with fuel cycles under national control.

Many discussions of a potential global nuclear expansion posit that uranium resources will run short unless the world moves to the “closed” fuel cycle. In the case of the once-through fuel cycle, as noted above, about 200 tons of uranium are mined and purified for every ton of material fissioned each year in a 1 GW reactor. This “inefficiency” has plagued nuclear engineers and reactor designers from the very beginning of the nuclear era. Already in 1944, a group of eminent scientists of the U.S. Manhattan Project devised the concept of the breeder reactor, which would produce more fuel than it consumes, because they were concerned that uranium might be too scarce to build even a small number of bombs.¹⁹ And since the 1950s, several countries have launched plutonium breeder reactor programs, motivated in part by concern that deposits of high-grade natural uranium ore might become scarce as nuclear power expanded.²⁰

The argument for reprocessing based on the scarcity of uranium, however, is a weak one. Plutonium fuels will remain non-competitive compared to uranium fuels until the price of uranium increases to more than \$500/kg of uranium, about four times its price today.²¹ The estimated global reserve is sufficient to fuel thousands of reactors. Even with a major expansion of nuclear power, availability and price of uranium will not significantly affect the viability or competitiveness of the once-through fuel cycle through 2050 and probably even beyond.

Unlike reprocessing, uranium enrichment is an essential part of the nuclear fuel cycle today.²² As with reprocessing, however, even a relatively small enrich-

ment plant is sufficiently large to support a significant military program. A standard 1 GW reactor requires about 20 tons per year of low-enriched uranium (LEU), which in turn requires 200 tons of natural uranium input to an enrichment plant. The same enrichment plant (the size that Brazil and Iran are currently building) with the same natural uranium input can be used to produce about 600 kg per year of weapons-grade highly enriched uranium (HEU), enough for 25 to 50 weapons per year.

Centrifuge enrichment plants now dominate the modern nuclear fuel cycle, even though it was always understood that the technology is highly proliferation prone.²³ They can be converted quickly from production of LEU to production of HEU.²⁴ And they can be built clandestinely, a primary concern with Iran’s program today.

Even if we assume that the accumulation of separated plutonium can be stopped in a world with a greater role for nuclear power, we are left with the problem of the spread of other sensitive nuclear-fuel-cycle technology (notably, centrifuge enrichment) to non-weapons states. Multinational ownership and control of sensitive fuel-cycle facilities would therefore seem to be a necessary element of a world where nuclear power is deployed widely but risks of nuclear war and nuclear terrorism are smaller than today.

Can nuclear power be decoupled from nuclear weapons? From the very beginning of the nuclear age, it was understood that allowing nuclear facilities to operate under national control, even under international monitoring, carried serious risks. Nonetheless, civilian nuclear energy use and related proliferation risks received little attention for the first 25 years, while the nuclear arms race of

the two superpowers was unfolding and the weapons programs in other countries were largely unconstrained.

The debate over alternative, multilateral approaches to the nuclear fuel cycle first engaged the world in the mid-1970s, and is now with us again.²⁵ The nuclear industry, however, has traditionally been reluctant to acknowledge the connection between civilian and military use of nuclear energy. The Director General of the World Nuclear Association, an industry lobby group, recently said, “[T]he global non-proliferation and safeguards system effectively curtails any link between civil and military programs.”²⁶ He added, “[W]hatever proliferation risk we face would be unaffected even by a 20-fold increase in the global use of safeguarded nuclear reactors.”

What degree of decoupling of nuclear power from nuclear weapons could be accomplished with multilateral approaches? To answer this question, one must consider the points of view of both providers and recipients of nuclear technology.²⁷

Nuclear-supplier states and today’s nuclear-weapons states emphasize the objectives of preventing the further spread of sensitive nuclear technologies and of ensuring that they are used only for peaceful purposes where they remain. Many states, however – in particular, recipient and non-weapons states – have different priorities. For them to support and participate in multilateral approaches and to forgo research and development of certain elements of the fuel cycle, they require specific incentives. Increased energy security through fuel assurances is often not one of them, because most states are already satisfied with the current market structure characterized by several independent and reliable fuel suppliers. The interests of many recipient states lie elsewhere.

Among many non-weapons states, there is broad dissatisfaction with the status and prospects of the Non-Proliferation Treaty (NPT). Their priority is limiting any differential nuclear weapons capability in their region, but they are also unhappy about the implementation of Articles IV and VI, which define rights and obligations with respect to peaceful use and disarmament.²⁸ The current system of supplier states, which is based in the nuclear-weapons states and a few closely allied countries, is seen as a major expression of a distorted implementation of Article IV.

Some proposals for multilateral approaches to the nuclear fuel cycle tend to increase this tension further by creating a two-tier world of “suppliers” and “users.” But other approaches recognize this dilemma. They envision a more active role for non-weapons states in the supplier market, for example, featuring participation in multinational enrichment plants.

Fuel-cycle facilities under multinational ownership and control are not a silver bullet, but they offer several important advantages vis-à-vis plants under national control. At a minimum, multinational plants can serve as a confidence-building measure through regional cooperation and make breakout politically more costly. Moreover, if sensitive technologies are used on a “black-box” basis, as they often are today in the case of centrifuge enrichment plants even in weapons states, participants would not unnecessarily acquire latent proliferation capabilities. Over time, multinational ownership and control could therefore alleviate concerns about parallel clandestine programs.

In support of sustainable one-tier arrangements, multinational ownership of fuel-cycle facilities in the nucle-

ar weapons states and supplier states will be a necessary complement to similar arrangements in non-weapons states and recipient states. Eventually, conversion of all existing national enrichment plants to multinational ownership and control will be required. Enrichment providers will not easily cede control of their existing facilities and place them in a new, and initially uncertain, institutional framework. However, if nuclear disarmament proceeds and deeper cuts in nuclear arsenals are agreed upon, the weapons states – all of which have built or are building large-scale uranium enrichment plants – would themselves have strong incentives to embrace multinational controls as a way to constrain national breakout capabilities and reduce the risk of clandestine enrichment plants.

Nuclear power will confront two major tests in the coming decade. First, issues related to coupling to weapons must be resolved. Second, the cost of nuclear electricity must be demonstrated to be competitive. How should this next decade be used? We identify four priorities.

First, to address the coupling to weapons, the once-through fuel cycle must become the norm. The trend of accumulating stockpiles of civilian plutonium must be stopped and reversed. Current reprocessing must be phased out so that there are no additions to the massive overhangs of separated plutonium now in place in countries that have been reprocessing, and work toward the safe disposal of existing separated plutonium stocks must begin. Moreover, all enrichment plants must be brought under effective multinational ownership and control.

Second, to improve the competitiveness of nuclear power relative to other sources of energy supply, reductions in

construction and operating costs will be required. Broadly based sharing of information about the construction of new nuclear power plants is in the interest of the industry; such sharing should result in a firm understanding of the costs when best practices are pursued.²⁹ Similarly, plant operation procedures for both new and existing plants (including operator training) could be coordinated internationally beyond the levels today.

Not much new capacity is likely to be added to the grid in this decade,³⁰ but the bottlenecks that today thwart expansion must be addressed. These include production of pressure vessels and other distinctive high-technology components, trained people, and regulatory and legal frameworks. To promote innovation and reduce concerns about the safety of older plants worldwide, incentives that today strongly favor plant-life extension should be revised in favor of retirement and new construction.

Third, during the coming decade, the social contract between the nuclear industry and the public regarding burdening future generations with the management of nuclear waste must be renegotiated, so that interim storage of nuclear waste can become the option of choice for at least several decades. Dry-cask storage can be widely implemented. Development and exploration of potential sites for long-term geologic disposal of nuclear wastes can continue, but with reduced pressure to authorize long-term repositories.³¹

Finally, research and development undertaken in the next one or two decades must support the transition to a nuclear fuel cycle compatible with nuclear energy on a larger scale and in more countries.³² Some of this activity must explore advanced safeguards techniques and further expand the idea of safeguards-by-design, which recognizes

that plant design can “facilitate or frustrate” IAEA safeguards efforts.³³

We end with four questions that we believe deserve much more discussion, and we provide tentative answers.

Will nuclear energy fare better in a world where climate change is a priority? Not necessarily. Climate-change policy could handicap fossil fuels but forcefully promote renewable energy and efficiency. Nuclear power’s short-term fate depends more on other factors, notably capital and operating costs, safety record, coupling to nuclear militarization, and the overall sense of competence and responsibility that the industry projects.

Can we have much more nuclear energy without nuclear disarmament? Only with great difficulty. A multilateral nuclear disarmament process might be the most effective way – perhaps the only way – for states to move away from enrichment and reprocessing plants under national control. Proposals for multilateral approaches to the nuclear fuel cycle need to take the nuclear disarmament process, rather than traditional nuclear nonproliferation efforts, as their main frame of reference.

Can we have nuclear energy in a nuclear-weapons-free world? A nuclear-weapons-free world would be more stable and more secure without nuclear energy. But a new framework for the nuclear fuel cycle could make nuclear energy compatible with a nuclear-weapons-free world.

Will the nuclear power cure for climate change be worse than the disease? Every

“solution” to climate change can be done badly or well. Done badly, it can be worse than the disease. Making climate change the world’s exclusive priority is therefore dangerous. It results in an overemphasis on speed of transformation of the current energy system and a dismissal of the very large risks of going too fast. Looming over energy efficiency is the shadow of excessive regimentation; over renewables, land-use conflicts (with food, biodiversity, and wilderness values); over carbon dioxide capture and storage, the environmental abuses that continue to characterize the fossil fuel industries; and over geoengineering, granting excessive authority to a technocracy. Looming over nuclear power is nuclear war.

The upper limits of climate change are terrifying, amounting to a loss of control of the climate system as positive feedbacks of various kinds set in. Nonetheless, at this moment, and conceding that such calculations can only embody the most subjective of considerations, we judge the hazard of aggressively pursuing a global expansion of nuclear power today to be worse than the hazard of slowing the attack on climate change by whatever increment such caution entails.

If over the next decade the world demonstrates that it can do nuclear power well, a global expansion of nuclear power would have to be – indeed, *should* be – seriously reexamined.

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ENDNOTES

¹ The authors have benefited from numerous suggestions from Zia Mian. We are also indebted to Jan Beyea, Harold Feiveson, Steven Fetter, José Goldemberg, Robert Goldston, Robert Keohane, Scott Sagan, Sharon Squassoni, and Frank von Hippel for close readings of an earlier draft.

- ² Shoibal Chakravarty, Ananth Chikkatur, Heleen de Coninck, Stephen Pacala, Robert Socolow, and Massimo Tavoni, "Sharing Global CO₂ Emission Reductions among One Billion High Emitters," *Proceedings of the National Academy of Sciences* 106 (29) (2009): 11884 – 11888; www.pnas.org/content/106/29/11884.
- ³ Stephen Pacala and Robert Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science* 305 (2004): 968 – 972. Here, we slightly redefine a wedge to refer to 4 billion tons of CO₂ per year not emitted in 2050, versus 1 billion tons of *carbon* not emitted *in 50 years* in the 2004 paper.
- ⁴ For the purposes of this paper it is a detail that the center of gravity of discussions since wedges were introduced in 2004 has moved toward tougher targets. The "two-degrees" target widely discussed today – an average surface temperature rise limited to 2°C greater than its pre-industrial value – requires that global CO₂ emissions fall to *half* of today's value by 2050. For such a tough target, less than 10 percent of the job is done by one wedge.
- ⁵ We define a large plant to be one with a capacity of 1,000 MW, that is, 1 GWe, and base load to mean operating 8,000 hours per year. Our reference base load coal plant, somewhat more efficient than the coal plant one can build today, emits 800 grams of CO₂ for every kilowatt-hour of electricity, or 6.4 million tons of CO₂ per year. The nuclear plant displacing the coal plant has life cycle emissions of about 50 grams of CO₂/kWh; its carbon intensity is 16 times less than a coal plant. Rounding off, 700 nuclear plants emit 4 billion tons less a year than 700 coal plants.
- ⁶ We assume today's coal and natural gas plants emit 1,000 and 500 grams of CO₂/kWh, respectively.
- ⁷ Think of a nuclear plant displacing a coal plant half the time and a carbon-free renewable power plant the other half of the time, or, equivalently, a nuclear plant displacing a natural gas plant. Confirming this view, in 2006 the carbon intensity of average power was 56 percent of the carbon intensity of coal power; International Energy Agency, *World Energy Outlook 2008* (Paris: OECD/IEA, 2008), www.worldenergyoutlook.org.
- ⁸ One terawatt-hour is 1 billion kWh.
- ⁹ *World Energy Outlook 2008*.
- ¹⁰ *The Future of Nuclear Power* (MIT, 2003), web.mit.edu/nuclearpower. In MIT's high-nuclear scenario, 14,100 TWh of nuclear power are produced in 2050, which corresponds to 1,760 GW of base load power running 8,000 hours per year. The MIT report calculates 1,609 GW of "equivalent capacity" by assuming constant output throughout the 8,760 hours of the year. The map rescales the MIT totals to 1,500 GW of base load power to match the deployment scale chosen here.
- ¹¹ International Atomic Energy Agency, *Considerations to Launch a Nuclear Power Programme*, GOV/INF/2007/2 (Vienna, Austria: IAEA, April 2007).
- ¹² Several nuclear reactors were attacked and destroyed while under construction (that is, without risking radiological contamination): Iraq attacked Iran's Busher reactors during the Iraq-Iran War; Israel destroyed Iraq's Osirak research reactor in 1981 and perhaps another reactor in Syria in August 2007. Attacks on operational reactors were also considered. In 1991, Iraq fired a Scud missile with a cement warhead at Israel, apparently in an attempt to damage the Dimona reactor. The United States considered destruction of North Korea's Yongbyon reactor in the early 1990s to prevent plutonium recovery from the irradiated fuel in the core. India and Pakistan are a notable exception: they have signed an agreement not to attack each other's nuclear installations in the case of war.
- ¹³ Separated means unaccompanied by large amounts of radioactivity, and therefore relatively easily accessed. Today, more than 1,500 tons of civilian plutonium have not been separated and are still in spent fuel.

- ¹⁴ Under the planned START Follow-on Treaty, the United States and Russia have agreed to reduce their strategic nuclear warheads to 1,500 – 1,675 by 2016. According to estimates by the Federation of American Scientists, however, each country is expected to retain a total of about 7,000 warheads since they will continue to have non-strategic warheads, weapons in reserve, and weapons awaiting dismantlement. The global stockpile of nuclear weapons could therefore be on the order of 15,000 warheads. In a subsequent reduction, the United States and Russia might reduce to 1,000 – 1,500 total warheads on each side, which could correspond to 4,000 nuclear weapons worldwide.
- ¹⁵ Breakout describes a scenario in which a host state begins production of fissile materials for weapons purposes (without concealing this effort) at a facility that was previously used for peaceful purposes.
- ¹⁶ International Panel on Fissile Materials, *Global Fissile Material Report 2008* (Princeton, N.J.: IPFM, October 2008), Appendix 1A; www.ipfmlibrary.org/gfmr08.pdf. Germany is the only country that managed to stabilize and gradually draw down its plutonium stockpile after having stopped shipping spent fuel for reprocessing (in France and the United Kingdom) in 2005.
- ¹⁷ This is a balanced thermal and fast reactor system in which the plutonium generated in the spent fuel from the fleet of light-water reactors is used to fuel a fleet of fast reactors operated in a burner mode. *The Future of Nuclear Power*, Appendix Chapter 4, 124 – 126.
- ¹⁸ Shirley Johnson, *The Safeguards at Reprocessing Plants under a Fissile Material (Cutoff) Treaty*, IPFM Research Report 6 (IPFM, February 2009), www.ipfmlibrary.org/rr06.pdf.
- ¹⁹ Among others, the group included Enrico Fermi and Leo Szilard. Catherine Westfall, “Vision and Reality: The EBR-II Story,” *Nuclear News* (February 2004): 25 – 32.
- ²⁰ Thomas B. Cochran, Harold A. Feiveson, Frank von Hippel, Walt Patterson, Gennadi Pshakin, M. V. Ramana, Mycle Schneider, and Tatsujiro Suzuki, *Fast Breeder Programs: History and Status*, IPFM Research Report 8 (IPFM, forthcoming).
- ²¹ For this estimate, we assume typical transaction costs for the various steps of the fuel fabrication process, in particular \$1,000/kg and \$1,500/kg for reprocessing and MOX fuel fabrication. For the methodology, see *The Future of Nuclear Power*, Appendix Chapter 5.D. Our value for reprocessing is conservative. For example, the levelized cost of reprocessing at Japan’s new reprocessing plant is about \$3,750/kg. In general, fuel costs of nuclear energy are small compared to capital costs. Costs of standard LEU fuel add up to about 0.9¢/kWh, which is on the order of 10 to 20 percent of the levelized cost of electricity from nuclear energy.
- ²² The most common reactor type requires LEU (3 to 5 percent uranium-235, as compared to 0.7 percent of this isotope in naturally occurring uranium). LEU is not usable for weapons, but the same enrichment facility can in principle produce weapons-grade HEU (for instance, 90 percent uranium-235). In principle, nuclear energy can be deployed and used without relying on enrichment or reprocessing. For example, Canada’s original CANDU reactor design, which is natural-uranium fueled and heavy-water moderated and cooled, requires about 25 percent less uranium than a typical light-water reactor.
- ²³ More than 25 years ago, Allan S. Krass and coauthors recommended a shift toward proliferation-resistant enrichment technology, with plants operated under the authority of an International Nuclear Fuel Agency (INFA). With regard to centrifuge technology, they concluded: “Unfortunately . . . a number of operating facilities already exist. Preferably, these facilities should be shut down and dismantled”; Allan Krass, Peter Boskma, Boelie Elzen, and Wim A. Smit, *Uranium Enrichment and Nuclear Weapon Proliferation* (London and New York: Taylor & Francis/Stockholm International Peace Research Institute, 1983); free electronic access at books.sipri.org. Besides centrifuge enrichment technology, there is now also renewed interest in laser isotope separation (LIS), a technology that has been explored off and on since the 1970s as a “next-generation” process for uranium enrichment. In July 2009, Global Laser Enrichment, a joint venture, submit-

ted a license application for a large laser-enrichment plant in the United States; if it decides to move forward, it wishes to begin commercial operation in 2012. Little is known about the details of the LIS process, and no dedicated IAEA safeguards approach now exists. It is likely that the technology will raise proliferation concerns similar to those of centrifuges.

- 24 Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation," *Science & Global Security* 16 (1–2) (2008): 1–25.
- 25 The current debate gained momentum in October 2003 when *The Economist* published an article by IAEA Director General Mohamed ElBaradei, in which he acknowledged the shortcomings of the current nonproliferation regime; "Towards a Safer World," *The Economist*, October 16, 2003.
- 26 John Ritch, *The Necessity of Nuclear Power: A Global Human and Environmental Imperative*, World Nuclear University, "Key Issues in Today's World Nuclear Industry," Balseiro Institute, San Carlos de Bariloche, Argentina, March 10, 2008, www.world-nuclear.org.
- 27 For detailed discussion, see: *Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report Submitted to the Director General of the International Atomic Energy Agency*, INFCIRC/640 (Vienna, Austria: International Atomic Energy Agency, February 22, 2005); Alexander Glaser, *Internationalization of the Nuclear Fuel Cycle*, International Commission on Nuclear Non-proliferation and Disarmament, ICNND Research Paper No. 9, February 2009; and Y. Yudin, *Multilateralization of the Nuclear Fuel Cycle: Assessing the Existing Proposals* (New York and Geneva: United Nations Institute for Disarmament Research, 2009).
- 28 From this perspective, Article IV is particularly unbalanced. Besides guaranteeing the "inalienable right . . . to develop research, production and use of nuclear energy for peaceful purposes without discrimination," Article IV also specifies that states with advanced nuclear technologies should cooperate in contributing to "the further development of the applications of nuclear energy for peaceful purposes, especially in the territories of non-nuclear-weapon States Party to the Treaty."
- 29 Broad international industry-government coordination is a prominent feature of efforts today to accelerate the commercialization of CO₂ capture and storage.
- 30 A new study by the U.S. National Academy of Sciences estimates that "as many as five to nine new nuclear plants could be built in the United States by 2020." The National Academy of Sciences and the National Academy of Engineering, *America's Energy Future: Technology and Transformation, Summary Edition* (Washington, D.C.: The National Academies Press, 2009), 112; www.nap.edu/catalog.php?record_id=12710.
- 31 Richard L. Garwin, "Reprocessing Isn't the Answer," *Bulletin of the Atomic Scientists* (August 6, 2009); www.thebulletin.org/web-edition/op-eds/reprocessing-isnt-the-answer.
- 32 For example, increasing the burn-up of standard LEU fuel could improve overall economics of the once-through fuel cycle and also reduce uranium requirements to some degree. Using thorium fuel in new light-water reactor types as a partial substitute for standard LEU fuel could be another productive field of mid-term research. If implemented sensibly, thorium use would also reduce the total amount of plutonium embedded in spent fuel from light-water reactors and perhaps reduce some proliferation concerns of the once-through fuel cycle.
- 33 Brian Boyer, "Facility Design Can Aid or Frustrate International Safeguards Efforts," *Nuclear Power International* (June 2009).