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Toward an Assessment of Future Proliferation Risk

A key question for nuclear nonproliferation efforts in the coming decades is what the risk associated with peaceful nuclear commerce will be and if this risk will increase from the current level. The history of nuclear power generation since World War II suggests that the answer will depend on the answers to two additional questions: How will nuclear technology evolve and be deployed?And how will governments and their stakeholders assess proliferation risk and then muster the political will and resources to prevent nuclear technology and materials from being used for nonpeaceful purposes?

When the age of the "peaceful atom" was launched in the late 1940s, it was obvious to all concerned that nuclear electric power would rely on the same science that the US government had used just a few years before to build weapons of mass destruction and unleash their deadly power on the populations of two Japanese cities.

But after postwar leaders vowed to deliver a civilizing nuclear future, it took technologically advanced countries another two decades to fully grasp that wares intended to serve peaceful nuclear applications harbor the potential for doing great harm. Enthusiasts of nuclear power promised a cheap source of energy having virtually limitless potential; many expressed relatively little concern about the risk of severe nuclear accidents and still less about the prospect that technology or materials might be misused to make nuclear weapons. During the late 1940s, a few individuals, including Bernard Baruch, Dean Acheson, and David Lilienthal, urged that an international authority be set up to control or own all the nuclear materials and technology that would be needed to make atomic bombs.

Their ambitions were not realized, but the creation of the International Atomic Energy Agency (IAEA) in 1958 and the entry into force of the Nuclear Nonproliferation Treaty (NPT) in 1970 were signposts of growing awareness that goods dedicated to peaceful uses could be diverted to make nuclear weapons. In 1974, India detonated a nuclear explosive made using a reactor supplied by Canada and heavy water supplied by the United States under bilateral peaceful-use agreements with India. At about the same time, a scientist serving Pakistan's nuclear program stole uranium enrichment know-how from a peaceful-use project in the Netherlands. Governments of nuclear supplier states, shocked by these events, thereafter more rigorously identified the proliferation risks associated with specific nuclear power generation and fuel cycle technologies. Since then, their assessments have served as the basis for today's decision-making on guidelines and procedures for safeguards, nuclear security, and nuclear export controls.

NUCLEAR POWER TECHNOLOGIES

For at least the next two decades, most types of materials, technologies, and installations used for nuclear power generation, including those for nuclear fuel processing and production, will not be very different from those in use today. Because the acceptance and dissemination of nuclear power technologies have been subject to industrial-commercial considerations and national government licensing requirements based largely on common norms and standards, these technologies have not evolved by leaps and bounds. As a consequence, knowledge about their risks – including proliferation threats – has increased over time. On balance, the risk portfolios of these technologies have become well understood, certainly compared to a half century ago. Knowledge has also increased as a result of significant proliferation events.

Power Reactors

Power reactors are the technology mainstay of electricity generation based on fission energy. As was the case during the last half century, in coming decades, most power reactors will be based on proven technology and fueled with uranium. More-innovative reactor designs are currently under development, but most of these have far to go before they can be realized.

Light-water reactors. Beginning in the 1950s, several reactor technologies were deployed for power generation, including some initially developed for production of plutonium for nuclear weapons. But over time, the light-water reactor (LWR) design emerged as the most common reactor type for making electricity. Today, and for at least a few decades to come, most of the 500 or so power reactors in operation and under construction will be LWRs, the majority of these pressurized-water reactors.

In NPT non-nuclear-weapon states, all reactors are subject to IAEA safeguards, including power reactors. These are fueled with fissile material, and the plutonium they generate in irradiated (or "spent") fuel can be used to make nuclear weapons. That said, LWRs have some features generally viewed as positive for nonproliferation: they normally operate using chemically stable uranium dioxide fuel enriched to a low level of enrichment level of about 5 percent uranium-235; they must be shut down to refuel; and the plutonium they generate in irradiated fuel is on balance less attractive for nuclear weapons than plutonium produced by some other reactor types and is more easily extracted.[1]

1. There is no question that plutonium produced in light-water reactors, once separated from the irradiated fuel through reprocessing, can be used to make nuclear explosives. The matter was considered extensively during conceptualization of the international project under the direction of the Korean Peninsula Energy Development Organization (KEDO) from 1994 until 2006. Participants concluded that compared to a natural-uranium-fueled, gas-cooled, and graphite-moderated reactor built by North Korea – based on a design used in the United Kingdom for plutonium to be used in nuclear weapons – the two LWRs foreseen under the KEDO project posed less proliferation risk (Abushady 2001).

The IAEA currently safeguards more than 200 LWRs; the rest are in nuclear-armed states. The fuel cycle for these reactors is well understood for purposes of safeguards, and the IAEA's analysis of nuclear weapon acquisition paths includes scenarios and technical indicators for fuel diversion (Harms and Rodriquez 1996, 16-19). To date, the IAEA has never concluded that plutonium has been diverted for the purpose of making a nuclear explosive from a safeguarded reactor dedicated to power generation.

Most power reactors were designed for an anticipated lifetime of 30-40 years; some units operating today may be relicensed to continue operating for 60 years or more. How long they operate will also depend on whether owners and governments conclude that continued operation is justified in light of market constraints and policies on electricity-generating fuels.

Fast-neutron reactors. Several advanced nuclear countries, including all five NPT nuclear weapon states, developed fast-neutron reactors (often known simply as "fast reactors") decades ago. These countries intended to separate the plutonium from irradiated power reactor fuel and use it as fuel in fast reactors, including to "breed" additional plutonium fuel – that is, to operate these reactors to produce more plutonium than they consume. By 2000, only France, Japan, and Russia had succeeded in operating industrial-scale prototype fast reactors and planned to build more units. Today, Russia is the only country operating a big fast reactor; it may soon be joined by India, which after years of delays is on the threshold of operating an initial industrial-scale unit. India plans to build additional fast reactors during the 2020s and beyond. Last year Russia halted its next scheduled project for at least a decade, apparently for cost reasons (World Nuclear News 2019). France in 2019 terminated its program for an industrial-scale reactor, and Japan's effort is also indefinitely stalled (De Clercq 2019; Japan Times Editorial Board 2020).

Today China is the only country building a new industrial-scale fast reactor, under a national research and development (R&D) blueprint to eventually replace LWRs with fast reactors after 2050 (Hibbs 2018, 29-32). Were China (or another country) to overcome the very severe economic and technical challenges of establishing a self-sustaining industrial-scale fast-reactor program using plutonium, this feat would be a game changer for nuclear power and a major challenge for efforts to restrain the technology ambitions of non-nuclear-weapon states and the spread of nuclear weapons. China has far less experience than France, India, Japan, or Russia with fast-reactor technology, operations, and advanced fuels; it is uncertain if China will commit sufficient resources for the decades needed to succeed in this undertaking.

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New reactor types? In coming decades, more reactors will likely appear that are not large-scale nuclear-power-generating units (over 500 megawatts [electric]), are not based on LWR technology, and may serve applications other than electricity. The nuclear industry's interest in small and medium-sized or modular reactors (SMRs) is driven by declining sales for large LWR power plants. Some SMR models are based on LWR technology. Others are concepts or preliminary designs; comparatively little is known about their potential proliferation risks. Some concepts are under development for use as "nuclear batteries" and for innovative fast reactors that may require reprocessing of irradiated fuel, depending on their mission. One concept for a molten-salt reactor involves breeding of thorium to produce the U-233 fissile isotope that in principle could be used to make nuclear explosives.

Since the 1970s, a few high-temperature gas-cooled reactors (HTRs) have been deployed; at least several more will likely be constructed. Some HTRs were fueled with highly enriched uranium (HEU); most of those that are under development feature pebble-type uranium fuel enriched to up to 20 percent U-235. For these reactors, irradiated fuel would be discharged and likely stored indefinitely, pending final disposal. In principle, the irradiated fuel can be reprocessed to recover fissile material, but HTR programs so far have paid comparatively little attention to a closed fuel cycle (see below) for these reactors.

Many non-LWR-type SMRs would likely require years of development and licensing before they could be deployed. China, for example, has invested heavily in molten-salt reactor technology but does not anticipate that a reactor will generate electricity before 2040. In the meantime, the IAEA is conferring with member states, and their R&D and industry firms, to encourage them to design safeguards systems for the fuel cycles for novel technologies in advance of project licensing and construction. Some reactor concepts call for longer duty cycles or lifetime fuel loads, which may reduce proliferation risk by limiting refueling operations and by increasing the "burn-up" level of the fuel, rendering it marginally less attractive for nuclear weapons. Unique proliferation risks may arise for some reactors whose deployments are not stationary.

Fuel Cycle Technologies

For 75 years the most significant proliferation challenges related to nuclear power followed from two activities: efforts to "close" the nuclear fuel cycle by recycling plutonium recovered at reprocessing plants from irradiated power reactor fuel, and enrichment of the U-235 isotope to make reactor fuel. The threat posed by reprocessing and plutonium use is that the plutonium could be diverted to make a nuclear weapon. The threat associated with uranium enrichment is that the technology can be used to clandestinely enrich U-235 for a nuclear weapon.

Reprocessing and plutonium recycling. From its inception, the nuclear power industry projected that conventional uranium-fueled reactors would be replaced by fast reactors that would breed their future plutonium fuel supplies. When fast-reactor prospects diminished, the industry focused more on recycle in LWRs of plutonium recovered from irradiated LWR fuel. For civilian nuclear power programs, plutonium is used in the form of so-called mixed-oxide (MOX) fuel, a mixture of UO_2 and PuO_2 fuels.

Today only France and Russia reprocess nuclear fuel on an industrial scale. Without a business case supporting the comparatively expensive recycling of nuclear fuel or continued significant French and Russian investment, the reprocessing industry will stagnate and may collapse. France's industry was supported in the past by lucrative foreign contracts, but in recent years its La Hague reprocessing complex has mostly reprocessed spent fuel from French LWRs (De Clercq 2015). Russian reprocessing is limited almost entirely to Russian reactor fuel.

In 2019, the uncertain future of this industry was underlined when the United Kingdom closed its Thermal Oxide Reprocessing Plant because clients had shifted their spent-fuel management

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policy from reprocessing and recycle to long-term spent-fuel storage (World Nuclear News 2018). France must likewise decide whether a planned investment in an expensive refurbishment at La Hague is justified. If not, France may abandon its commitment to the closed fuel cycle, and in the long term, all of the country's electricity might be based on existing reactors and renewable sources supported by batteries.[2] Russia, facing similar investment challenges, has decided to extend the lifetime of its reprocessing industry and will upgrade its RT-1 complex for operation until decommissioning in 2030 while building up a second reprocessing complex in Siberia. In tandem with Russia's decision to delay further fast-reactor development, the timetable for extending operation at nominal reprocessing capacity may be delayed for about a decade, according to some Russian sources; Russia has declared that the Siberian plant will begin operating in 2025.[3]

Uranium enrichment technology deployed for peaceful use has been repeatedly misused with intent to make nuclear weapons.

Plans elsewhere for industrial-scale reprocessing are uncertain. After 15 years, a project for a foreseen Franco-Chinese reprocessing plant in China has not been finalized.[4] Japan's efforts since the 1980s to build and operate a La Hague-scale complex have been dogged by politics, technical problems, cost overruns, and finally a severe nuclear accident at the Fukushima-Daiichi nuclear power plant that raised fundamental questions about Japan's nuclear future; Japan nonetheless continues with the commissioning of the reprocessing plant (Kotsubo, Kuwabara, Ito, and Hayashi 2020). The United States under President Donald Trump in 2020 has expressed interest in foreign reprocessing of irradiated US power reactor fuel, in a departure from long-standing US government policy and regardless of the apparent lack of interest by the US power industry. Beginning in the 1950s, India has operated several limited reprocessing installations, including to support its fast-reactor program; so far India has not attempted industrial-scale plutonium separation.

Current demand for plutonium fuel is very modest; fewer than 10 percent of the world's reactors are licensed to burn MOX fuel. Through 2030, at least some recycle may be driven by requirements to reduce inventories of separated plutonium stored in the United Kingdom and France. Like France at La Hague, Russia at RT-1 has accumulated a huge inventory of separated plutonium during a half century of reprocessing. Russia has earmarked this plutonium for use in fast reactors, and some may be used at the BN-800 unit beginning in 2021. Historically, Russia's fast reactors have used mostly uranium fuel, in part out of consideration for the comparatively greater complexities of operating fast reactors using plutonium. Russia has long declined to recycle plutonium in LWRs, but with its plutonium stockpile continuing to expand, the policy may change. Should Russia succeed in routinely using large amounts of plutonium fuel in the BN-800, its biggest and most advanced fast reactor, it would move a step closer toward establishing a closed industrial nuclear fuel cycle. As with industrial reprocessing, industrial-scale fabrication of MOX fuel currently is limited to France and Russia, pending developments in China and Japan. A recent project to establish a US MOX industry failed, the outcome of partisan politics, ineffective oversight, and cost overruns (Holt and Nikitin 2017).

Uranium enrichment. Uranium enrichment technology deployed for peaceful use has been repeatedly misused with intent to make nucle-

2. French commitment to a closed nuclear fuel cycle, according to a French government nuclear official, will be subject to ongoing development of alternative power generation and storage technologies (Hibbs 2018, 108).
3. The International Panel on Fissile Materials currently estimates the throughput of the site as 250 metric tons heavy metal (MTHM)/year (IPFM 2020); according to an industry report, the plant will be finished in 2025 with throughput given as 700 MTHM/year (World Nuclear Association 2020).
4. China and France have routinely said that ongoing negotiations are the reason for the delay in this project. According to European officials in 2010, French government ministries raised national security concerns that led France to condition the sale of the reprocessing plant to China upon steps taken by China to assure that the plant and its technology will not be used for nonpeaceful purposes (Hibbs 2018, 38-39, 119 [note 103]).

ar weapons. Between 1970 and 2000, several countries acquired gas centrifuge enrichment technology stolen from Europe. Iran, Iraq, Libya, North Korea, and Pakistan are confirmed to have obtained this purloined know-how; according to unconfirmed information, more states may currently have it. This stolen know-how has been replicated, including using digital electronic means, and it remains at large. In the future, it could be used by proliferators to make nuclear weapons. National governments and industry responded to these events by strengthening controls and security concerning equipment, technology, and materials for enriching uranium. Since 1997, countries whose IAEA safeguards agreements include an Additional Protocol are obligated to declare more fuel-cycle-related activities, including those connected with uranium enrichment.

Argentina, Brazil, China, France, Germany, India, Iran, Israel, Japan, the Netherlands, North Korea, Pakistan, Russia, the United Kingdom, and the United States host uranium enrichment plants. Some are dedicated to military use and some enrich uranium only for peaceful uses; all of the peaceful-use plants in states without nuclear arms are under multilateral safeguards. Enrichment capacity dedicated to peaceful uses has exceeded demand for many years and may continue to do so for some time to come, partly as a consequence of the Fukushima-Daiichi accident in Japan. Several enrichment technologies have been used, beginning during World War II, but in recent decades, less efficient gaseous diffusion technology has been supplanted by gas centrifuge technology. The centrifuge will likely continue to serve as the leading industrial-scale uranium enrichment technology.

For half a century, the uranium enrichment industry has experimented with alternative technologies, especially laser excitation, but nearly all these efforts were abandoned on economic grounds. During the last decade, investors in Australia, Canada, Japan, and the United States developed a molecular laser enrichment technology that has been licensed in the United States for operation of a test loop (APS News 2010). If this project inspires greater interest, a proliferator might attempt to use lasers to produce U-235 for nuclear weapons.

THE NUCLEAR POWER MARKET

Within three decades after World War II, firms in advanced nuclear countries were selling their goods to established domestic markets for nuclear power and also exporting power plants, research installations, fuel processing plants, and nuclear fuel to more than 100 countries. Much commerce in radioactive and nuclear materials, nuclear technology, and nuclear equipment was for non-power applications and research; however, nuclear power proved its value in a number of advanced countries and by 1980 was expanding to new markets in South America, Africa, and Asia. But before the end of the century, governments and the IAEA were increasingly concerned about the levels of safety and security at 200 uranium-fueled research reactors worldwide, of which scores were idled or underused and some woefully maintained. Severe accidents and the impact of the introduction of market forces in power markets revealed the risks and raised the costs of nuclear power projects; potential "nuclear newcomers," including rapidly growing developing countries, considered these risks in weighing their options for power generation. During the 1990s, the nuclear power industry began predicting a nuclear power "renaissance." This had not yet transpired when in 2011, Asia's richest, most technologically advanced, and most nuclear-experienced country failed to prevent three LWRs at the Fukushima-Daiichi site from melting down within 72 hours in a severe nuclear accident that was ultimately caused by human error (Acton and Hibbs 2012a; Acton and Hibbs 2012b).

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Since the 1980s, as the costs and risks of nuclear power projects have increased, the nuclear industry has undergone uninterrupted global supplier consolidation. Forty years ago, there were about two dozen vendor companies in advanced nuclear countries building nuclear power plants; today about one-third that number are active worldwide. When governments in the 1980s began deregulating their electric power sectors, market share for new fossil-fuel power plants increased. Ever-fewer nuclear power plants were ordered, and vendors lost expertise, contributing to significant cost overruns for the handful of ongoing plant construction projects in Europe and the United States during the last decade.

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In recent years, a few new suppliers have emerged, notably in South Korea. But most of the world's construction of new nuclear power plants in this century has been undertaken by companies in China – a development that underlines both the aspirations and the problems that will challenge the global industry during the 2020s and perhaps beyond. In 2005, China launched a crash construction program to catch up with advanced countries; today it is operating more than 50 nuclear power plants. But as was the case in the advanced nuclear countries whose reactor deployment China has replicated, it is not apparent that China's rapid nuclear expansion will be indefinitely sustainable. There are a number of reasons for this: Beijing planners, aiming to control and reduce the cost of electricity, are pressing for power market reforms that in the United States and Europe previously precipitated a crisis in the nuclear power industry. China's nuclear vendor firms have reached, and in some cases exceeded, the liability limit imposed by their government financial shareholder; this implies that China's rising debt load, on top of slower power demand growth, may discourage new nuclear investments by these firms, especially if rising production costs and regulation render new nuclear investment comparatively less lucrative and if China's powerful fossil-fuel industry resists pressure to downsize. Finally, since Fukushima, nuclear plant construction on inland sites has been a Chinese political redline. It is not clear whether China's decade-long race for nuclear capacity portends a second wind for nuclear power beginning sometime in the 2020s or instead will be followed by the saturation and crisis that other countries have experienced, albeit not until the 2030s with perhaps more than 100 power reactors on line.

The continued depression in demand for nuclear power plants also reflects rising expectations that renewable sources – chiefly wind, solar, and hydropower – will supply more and more power to meet future demand growth. According to some projections, global power generation may nearly double by 2050, and nearly all of the increase will be produced by renewables (US EIA 2019). Some forecasters also predict that in places where nuclear power is well established – for example, in Europe, Russia, China, and South Korea – by 2050, the nuclear share of total power generation will remain at or near current levels (IAEA 2018). A key question is whether countries with long-standing nuclear programs will build new nuclear power plants to replace aging and less competitive capacity. If not, nuclear power output in the United States, France, and Japan – in recent decades the world's leading nuclear-power-producing states – may decline through about 2030, putting vendor firms in these countries under still greater pressure to find foreign markets.

In this situation, the US nuclear industry is pressing the federal government to provide it financial assistance to compete with state-owned enterprises (SOEs) in China and Russia that benefit from government aid in securing contracts, subsidized financing, and price supports for nuclear power (Marshall and Dillon 2020). The leading US vendor, Westinghouse, was awarded its most recent nuclear power plant contract in 2007 (Schepers 2019, 3). By comparison, Russian vendor Rosatom in 2017 claimed to have foreign order books worth $133 billion, lifted by sales contracts for

36 nuclear power plants in 12 countries including Armenia, Bangladesh, Belarus, China, Egypt, India, Turkey, and Uzbekistan (Schepers 2019, 4). Chinese industry, which until now has exported nuclear power plants only to Pakistan, aims in the coming years to build more than 20 nuclear plants for export, including through China's Belt and Road Initiative. These exports are to be bolstered by an active supply chain China has been setting up and expanding since the early 2000s (Hibbs 2018, 90-92).

The future of Chinese exports – not only in the nuclear sector – will depend in part on the goodwill of foreign governments and in part on the capacity utilization of Chinese industry. Beginning with agreements forged between Chinese SOEs and partners in the United Kingdom, China in the 2020s aims to sell its nuclear power plants in established, advanced-country nuclear markets. That may not be likely if great-power competition between China and the West increases, fed by allegations of Chinese cyberattacks and industrial espionage, including against foreign nuclear power companies and other "strategic" targets (US DoJ 2014). In 2018, the US government announced that, because of China's pursuit of "military-civil fusion" in its foreign nuclear trade, the United States will, with few exceptions, deny bilateral nuclear commerce (US DoE 2018). If China is increasingly perceived to be an aggressive adversary and US policy has a signal effect, Chinese nuclear power plant exports, and bilateral industrial and R&D cooperation with Chinese organizations, will be judged around the world as net security risks. Independent of China's foreign relations, China's drive for nuclear exports will also be affected by capacity utilization of China's nuclear industry. This was built up during the last 20 years on the foundation of ambitious expectations for as many as 500 reactors installed by 2050. Should instead China demand less nuclear power, its firms will be under pressure to export to take up the slack.

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Unlike Chinese firms, Rosatom currently has contracts for foreign nuclear construction projects that may occupy it beyond 2030. But at least some of these may not prove sustainable, as they follow from "framework" cooperation agreements sought by Moscow with developing countries. Rosatom has long had a dual identity. On the one hand, the firm profits from routine market-driven business for domestic new power plants plus fuel and services for operating plants worldwide; on the other hand, it is the implementer of the Kremlin's "strategic" trade agreements that without sovereign guarantees would be fraught with project risk. Following from one such arrangement, Russia is assuming most of the risk to build, operate, and own nuclear power plants in Turkey. Rosatom's contracts to supply nuclear power plants to Bangladesh and Egypt rest upon massive Moscow-backed credits. It may be speculated that the Kremlin's political power structure discourages information flow from corporate management that would inform President Vladimir Putin of the project risk attached to "strategic" foreign trade deals he is making (Stanovaya 2020).

Elsewhere, firms in the nuclear power industry face similar challenges in their important markets. South Korea's nuclear export industry expanded on the basis of serial domestic power plant construction, but the growth in South Korea's demand for power is slowing, raising pressure to export. For decades, the centerpiece of India's nuclear industry was technology copied from its pre-1974 cooperation with Canada. Beginning in the mid-2000s, the United States aimed to end India's isolation from the world's nuclear power business following India's 1974 and 1998 nuclear tests, but so far nuclear power industry cooperation between India and most foreign partners is bedeviled by liability considerations.

The ongoing drought in new business for builders of nuclear power plants has raised the specter of technological obsolescence. For over a decade, France has tried with little success to sell and build its EPR nuclear power plant. When the United Arab Emirates instead selected Korean firms, senior French officials claimed that the EPR — a hybrid Franco-German model from the 1990s — was myopically designed for European safety concerns and too big for modest power grids (NS Energy 2010). Similar thinking with regard to size may be advancing in the United States, where, in the absence of orders for big LWRs, the industry is embracing SMRs.

OUTLOOK

The nuclear power industry is mostly conservatively biased in favor of established technologies for which the proliferation risk is well understood; this knowledge serves as the basis for the deterrence of nonpeaceful uses. Risks associated with nuclear fuel cycle technology are more acute than with technology for power reactors. Great concern will remain focused on uranium enrichment, know-how for which has been stolen and may be further proliferated through clandestine transactions. Threats from reprocessing arise in part because chemical separation technology for many decades has been openly accessible. Proliferation risk will be greater if demand for nuclear power increases and the industrial fuel cycle is closed. Risk may also increase should the global nuclear industry shrink further and discharged personnel with sensitive know-how seek employment by proliferators. Effective management of proliferation threats will require a continuity of international governance; this will rest upon states' nuclear restraint and their support for effective IAEA verification.

Technology and Materials

Because nuclear power technology has evolved very slowly since the middle of the last century, the inherent risks from technologies and materials used for nuclear power generation and the nuclear fuel cycle in coming decades will likely not be very different from those encountered so far. (Some critics believe that the industry's failure to dramatically innovate means that nuclear power will become obsolescent during this century.) Most of the operating reactors in the world in 2035 will probably be LWRs, even if some of those are SMRs. A small number of reactors fueled with natural (unenriched) uranium will continue to operate in a few locations. So long as the NPT remains a virtually universal treaty, all reactors in non-nuclear-weapon states will be under multilateral safeguards. Modern nuclear power plants are highly complex, expensive engineering projects that must meet international standards for quality and safety involving IAEA and global industry peer reviews. Innovations in manufacturing, materials, construction, and information management will not likely significantly alter their risk profiles, provided that government safety and security oversight keeps abreast of developments.

Since the 1980s, governments and the IAEA have become increasingly sensitized to the proliferation risks of reactor designs and fuel cycles. The more that agencies responsible for oversight, licensing, and nuclear material accounting and control are involved in the design of new reactors, the lower the concomitant risk will be. If vendors do not cooperate with the IAEA on "safeguards by design," proliferation risk associated with innovative technology may be greater. Because the SMRs most likely to be built soonest will probably be LWRs, they will pose few unfamiliar technology-based proliferation challenges. For others, including nuclear batteries, innovative fast reactors, and molten-salt reactors, the risk will depend on their "safeguardability" and whether their fuel cycles require reprocessing and direct-use fissile materials.

The proliferation risk associated with the operation of peaceful-use reactors should recede in part because fewer units will be operated using HEU fuel. Also, some national research programs and fuel processing and storage activities have been consolidated; some reactors have been converted to use low-enriched uranium fuel; and some HEU inventories have been repatriated to the United States and Russia, which in the past supplied HEU to their nuclear cooperation partners without great concern.

Reducing the amount of plutonium circulating in the fuel cycles of power reactors should also decrease proliferation risks. The benefit could be significant if, following the 2018 example of the United Kingdom, the civilian reprocessing industry continues to wind down and if electricity producers are discouraged by the comparatively high cost of using plutonium in their reactors. Forthcoming French decisions may be critical, as France's reprocessing sector and fast-reactor program are in a deep crisis that might lead Paris to abandon them in the coming years.

On the other side of the ledger are developments in China, India, Japan, Russia, and South Korea. Independent of plans to accelerate domestic reprocessing, Japan is storing in Europe 45 metric tons of plutonium separated from its irradiated LWR fuel. If this material reenters the civilian nuclear fuel cycle, short-term proliferation risk will increase; perhaps the very long-term risk would be marginally reduced because less separated plutonium would be stored. Russia and China are intensifying a bilateral partnership for the development and deployment of technology to close the nuclear power fuel cycle. Russia has announced progress in the development of advanced fuels using products from reprocessing and plans to market these fuels.[5] Regardless of long delays following in part from decades-long diplomatic isolation, India continues to aspire to a nuclear energy future centered upon industrial use of plutonium fuel. On balance, in view of costs and technical challenges, there is little reason to expect that China, India, or Russia will create a self-sustaining nuclear power industry centered upon plutonium-fueled fast reactors before 2050. But if any of them does, the proliferation risk from nuclear power may rise considerably, in part because other states will be encouraged to engage in sensitive nuclear activities. South Korea has been developing technology for a high-temperature electrochemical process called pyroprocessing to use on its irradiated LWR fuel. Some metallurgical know-how for this technology might be applicable in a nuclear weapon development program. Deployment of pyroprocessing so far has been inhibited by the realities of Seoul's bilateral nuclear energy and security cooperation with the United States, in which regional political and proliferation concerns play an important role.

Several hundred power reactors worldwide will continue to require enriched uranium fuel. Advanced nuclear states have in the past permitted gas centrifuge technology to be diverted from their peaceful-use nuclear programs to black market networks that have served proliferating states; governments and the IAEA therefore have few defenses today against the continued clandestine spread and use of centrifuge know-how that the proliferators have acquired in this way. The IAEA is concerned about the prospect that so-called 3D printing or additive manufacturing techniques, and the underground internet, or darknet, may contribute to proliferators' efforts to defeat nuclear trade controls.

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Should laser enrichment research resume, inspired by current (so far limited) commercial interest, the proliferation risk associated with uranium enrichment may increase.

In a singular exception among countries that export nuclear equipment, Russia has agreed in principle to take back spent fuel from power reactors it supplies to foreign clients, continuing a nonproliferation policy from the Soviet period. Should global competition among nuclear power plant vendors intensify, other supplier states might follow Russia's example. If so, pressure on countries operating nuclear power plants to reprocess

5. In the future, Russia may offer its foreign clients nuclear fuel made from uranium and plutonium that is recovered from reprocessing and that it claims is less weapon-usable than plutonium in MOX. In any case, this fuel may prove more expensive to produce than conventional LWR fuels (Federov, Dyachenko, Balagurov and Artisyuk 2015).

ever-growing stockpiles of civilian irradiated fuel and recycle the plutonium may be reduced.

Governance and Nuclear Power Demand

Sixty years ago it was frequently assumed that within a few years, the number of nuclear-armed states might rapidly increase, as John F. Kennedy had said during the 1960 US presidential debates, from four countries to 20 (Anderson 1997; CEIP 2003). By the beginning of the 1970s, all atomic-armed states but China were generating nuclear power, and numerous countries that were targets of speculation regarding suspected nonpeaceful nuclear intentions had already launched nuclear power programs: Argentina, Brazil, West Germany, India, Italy, Japan, South Korea, Pakistan, South Africa, Sweden, Switzerland, and Taiwan. While the roll of nuclear-power-generating states has expanded since 1970 from 13 to 35, the number of nuclear-weapon-possessor states has risen from five to nine. Horizontal proliferation was limited in part because other states, citing the rules and principles of international nuclear governance, intervened.

Beginning in the 1950s, budding nuclear supplier states agreed to establish a system of multilateral governance for the peaceful use of nuclear energy. This had many rationales, but in the shadow of an ideological Cold War joined between East and West, many governments — not least the United States and the Soviet Union — were mindful that geostrategic competition might ensue over the dissemination of nuclear materials and technology. The NPT became the centerpiece of nonproliferation governance; it provided supplier states a reference point for conditioning exports, especially of sensitive fuel cycle items. As the nuclear power industry expanded, membership in the Nuclear Suppliers Group (NSG), the world's leading nuclear trade regulator, increased from seven to 48, assuring that nearly all foreign nuclear commerce involving states without atomic arms would be subject to rules set by the NPT and the NSG to limit risk. Between the 1970s and 2000s, a raft of significant horizontal proliferation events, involving lax nuclear trade controls and undeclared, clandestine activities to defeat safeguards, led governments and the IAEA to raise the bar. In 1997, they created an Additional Protocol for safeguards, giving the IAEA greater authority in participating states to pursue information indicating that states may be engaged in clandestine activities. Since then, most states subject to IAEA safeguards have agreed to accept the Additional Protocol as an obligation.

> ***If Chinese and Russian firms eclipse US and other Western competitors in the world's nuclear power market, Beijing and Moscow will demand, and expect to obtain, primacy in nuclear energy governance that Washington and its allies have long enjoyed, especially during critical formative years.***

During the 2020s, the fabric of existing collective multilateral understandings about preventing proliferation may come under pressure. Today, the US nuclear industry and the US government claim that state capitalism in China and Russia threatens US leadership in nuclear power. If Chinese and Russian firms eclipse US and other Western competitors in the world's nuclear power market, Beijing and Moscow will demand, and expect to obtain, primacy in nuclear energy governance that Washington and its allies have long enjoyed, especially during critical formative years. The impact of such a shift could be significant. Russia has increasingly accused the West of imposing a "rules-based order" on other countries — shorthand for principles of conduct that serve Western interests (Lavrov 2019). China, which generated no nuclear power until the mid-1990s, "may conclude that it wants to change the rules, because when the rules were made China wasn't sitting at the table," as one Western official put it at a 2011 meeting for governments that participate in the NSG.

China and Russia, perhaps in alliance with other states, may increasingly challenge Western leadership at the IAEA and in other multilateral nuclear forums. Since the 2010s, both countries have objected to Western-favored resolutions concerning IAEA nuclear verification (Hibbs 2020). Big-power competition has also invaded NSG decision-making on the question of including India (Hibbs 2017). Some participants in the NSG and in the Convention on Nuclear Safety, an IAEA-based treaty, privately express great concern about a future "race to the bottom" over nuclear governance standards if states aggressively support selected "champion" vendor companies. Should the United States continue to lose influence in the greater Middle East or disengage from that area, Russia or China (or both) might emerge as a brokering power in nonproliferation in a region fraught with nuclear tensions involving Iran, Israel, and Saudi Arabia.

If the center of gravity in the global nuclear industry shifts toward China and Russia, that does not categorically imply that proliferation risks will be greater because the West will have comparatively less to say. Neither Russia nor China can be interested in a world with more nuclear-armed states. If the multipolar strategic competition between Western states on the one hand and Russia and China on the other is successfully managed in the coming decades, Beijing and Moscow might raise their nonproliferation profiles as their stake in the international system increases, thereby contributing to continuity in multilateral governance.

But in a more aggressive international environment, a shift in global nuclear governance power away from the Western states that for years have frequently taken the initiative on setting the rules might contribute to an erosion of states' participation in, or tolerance of, nonproliferation understandings. That could happen if Western states and rising powers fall out over how a more ambitious IAEA conducts verification, and if rising powers see multilateral nuclear governance as a theater to try to reduce Western influence, perhaps with the support of the majority of countries that have little stake in the nonproliferation regime. If this happens, global support for IAEA efforts to deter undeclared activities may decline, Western states' embrace of nonproliferation may be judged by others as an expression of self-interest, big powers may intervene in the UN Security Council to shield their allies from accountability, and more opportunistic or strategic nuclear commerce outside of NSG rules may be tolerated. Without a shared view that the nonproliferation regime must be strengthened and adjusted to meet evolving threat scenarios, a static and defensive approach to states' nonproliferation obligations, framed by governments' assertions of their "nuclear rights," may gain ground. A looming question is whether Iran's 20-year challenge to the nonproliferation regime will prove an isolated case or instead will encourage other NPT parties to conclude that they have greater leeway to hedge, and potentially a great deal to gain, by engaging in sensitive nuclear activities. ■

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