

MARK HIBBS

THE FUTURE OF
.....
NUCLEAR POWER
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IN CHINA



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CARNEGIE
ENDOWMENT FOR
INTERNATIONAL PEACE

The investigation leading to the publication of this report was generously supported by a grant from the John D. and Catherine T. MacArthur Foundation in Chicago, Illinois.

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ABOUT THE AUTHOR

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Hibbs' research is focused on international nuclear trade and nonproliferation governance in four main areas: the international nuclear trade regime, decisionmaking at the International Atomic Energy Agency, nuclear safeguards and verification, and bilateral nuclear cooperation arrangements.

In 2011 and 2015, Hibbs chaired two workshops for all participating governments of the Nuclear Suppliers Group, the world's leading multilateral nuclear trade control mechanism. He also authored a Carnegie report, *The Future of the Nuclear Suppliers Group*, published in 2011.

Hibbs also carries out policy research concerning the generation of nuclear power. In 2012, Hibbs co-authored with James Acton a report on *Why Fukushima Was Preventable*. Since 2011, Hibbs has led a project at Carnegie concerning the future of China's nuclear energy program and its nuclear fuel cycle policies. In 2014, Hibbs authored a study on Turkey's policies concerning the Nuclear Nonproliferation Treaty and the Nuclear Suppliers Group as part of a project called *Turkey's Nuclear Future*.

Hibbs has also contributed to articles and commentary that have appeared in the *New York Times*, *International Herald Tribune*, *Chosun Ilbo*, *Financial Times*, *Le Monde*, *Mainichi Shimbun*, *Frankfurter Allgemeine Zeitung*, *Washington Post*, and other media. He has also been a frequent contributor to the *Arms Control Wonk* blog.

GLOSSARY OF TERMS

Actinides

The actinides are heavy metallic elements with atomic numbers from 89 to 103. They are produced when uranium-based fuel is irradiated in a nuclear reactor, are radioactive but generally long lived, and are considered part of the waste stream. Plutonium and uranium are called the major actinides; the minor actinides consist of all other actinides, including neptunium, americium, and curium.

Base load

The base load is the minimum level of power that a power grid must supply over long periods of time, often conceived as the power output that is required 24/7. Base load contrasts to peak load, which is the maximum level of power a grid must supply for a short period of time.

Breeding ratio

The breeding ratio is the ratio of fissile material obtained to fissile material used after the irradiation of fuel in a reactor.

Burnup

Burnup refers to the amount of energy that is provided by an amount of nuclear fuel. For power reactors, a common measure of burnup is megawatt-days (or gigawatt-days) per metric ton of heavy metal. Burnup is one measure of the fuel efficiency of a power reactor.

Fast neutron reactor

A fast neutron reactor, or fast reactor, uses fast neutrons to generate a fission chain reaction. Thermal reactors, by contrast, contain a moderator (such as water or graphite) to slow the neutrons.

Fission products

Fission products are light elements, including isotopes of iodine, cesium, strontium, and xenon, produced when uranium-based fuel is irradiated in a nuclear power reactor. They are radioactive and are considered part of the waste stream.

Gigawatt

A gigawatt (GW), equivalent to one billion watts, is a standard unit used for measuring the electric power rating of industrial power plants. A gigawatt is enough power to illuminate 10 million light bulbs, each rated at 100 watts.

Heavy metal

Heavy metal refers to the actinides present in nuclear fuel. The quantity of bulk amounts of nuclear fuel is commonly measured as metric tons of heavy metal (MTHM).

Lanthanides

Lanthanides are fifteen so-called “rare earth” metals grouped on the periodic table of the elements as having atomic numbers 57 through 71. Some of these are generated as fission products in spent nuclear fuel.

Light water reactor

The light water reactor (LWR) uses low-enriched uranium dioxide fuel, and light water (i.e., normal water, not heavy water containing more of the deuterium hydrogen isotope) serves as both the core coolant and the moderator of the nuclear chain reactions. It is the most common type of nuclear power reactor.

Mixed oxide fuel

Mixed oxide (MOX) fuel contains both uranium dioxide (UO_2) and plutonium dioxide (PuO_2). It can be used in both light-water reactors and fast neutron reactors; the plutonium content in MOX fuel for fast reactors is generally higher than for light-water reactors.

Moderator

A moderator is a substance that slows down fast neutrons generated in nuclear fission reactions to permit them to be used in thermal reactors. The most common moderator in commercial power reactors is light water.

Neutron capture

Neutron capture happens when a neutron collides with a heavy nucleus and is absorbed by it. In a nuclear reactor, capture of neutrons by uranium leads to the transmutation of uranium into plutonium.

Pressurized water reactor

A pressurized water reactor (PWR) is a type of LWR in which water under high-pressure absorbs heat before being fed into a steam generator. It contrasts to a boiling water reactor, in which steam is produced directly in the reactor core.

Radiotoxicity

Radiotoxicity is the measurement of the adverse human health effects of a radionuclide due to its radioactivity, taking into account the type of radiation, its tendency to be absorbed by human tissue, and residence time in the body

Solvent extraction

Solvent extraction is a technique used in reprocessing to separate and purify plutonium and uranium from other substances in spent fuel.

Steam generator

Steam generators, which are used in PWRs, remove heat from high-pressure water and use it to boil low-pressure water, producing steam. The steam is then fed into a turbine used to generate electricity.

Supercritical water-cooled reactor

A supercritical water-cooled reactor is a concept reactor that would use water at such a high temperature and pressure that the liquid and gas phases are no longer distinct.

Thermal reactor

A thermal reactor is a reactor that uses slow neutrons.

Transuranic elements

Transuranic elements are heavy elements with atomic numbers higher than uranium (92).

LIST OF ABBREVIATIONS

| | |
|---------------|---|
| ADS | Accelerator-Driven System |
| CAS | Chinese Academy of Sciences |
| CAEA | China Atomic Energy Authority |
| CDFR | China Demonstration Fast Reactor |
| CEFR | China Experimental Fast Reactor |
| CGN | China General Nuclear Power Group |
| CGNPC | China General Nuclear Power Holding Company Limited |
| CIAE | China Institute of Atomic Energy |
| CNNC | China National Nuclear Corporation |
| COEX | Co-Extraction of Actinides |
| CSGC | China State Grid Corporation |
| ERI | Energy Research Institute of the NDRC |
| GDP | Gross Domestic Product |
| GIF | Generation IV International Forum |
| GNEP | Global Nuclear Energy Partnership |
| GWd/MT | Gigawatt-Days Per Metric Ton |
| GWe | Gigawatt (electric) |
| HEU | Highly Enriched Uranium |
| HLW | High-Level Waste |

| | |
|-----------------------|---|
| HTGR | High-Temperature Gas-Cooled Reactor |
| IAEA | International Atomic Energy Agency |
| IHEP | China Institute of High-Energy Physics |
| INPRO | International Project on Innovative Reactors and Fuel Cycle |
| kg | Kilogram |
| KWh | Kilowatt-hour |
| LBNL | Lawrence Berkeley National Laboratory |
| LWR | Light Water Reactor |
| MA | Minor Actinides |
| MEP | Ministry of Environmental Protection |
| MOX | Mixed Oxide |
| MSR | Molten Salt Reactor |
| MT | Metric Ton |
| MTU | Metric Tons of Uranium |
| MTHM | Metric Tons of Heavy Metal |
| MWt | Megawatts Thermal |
| NDRC | National Development and Reform Commission |
| NEA | National Energy Administration |
| NNSA | National Nuclear Safety Administration |
| NPT | Treaty on the Non-Proliferation of Nuclear Weapons |
| NSG | Nuclear Suppliers Group |
| OECD | Organization for Economic Cooperation and Development |
| P&T | Partitioning and Transmutation |
| PUREX | Plutonium Uranium Redox Extraction Process |
| PWR | Pressurized Water Reactor |
| R&D | Research and Development |
| REPU | Reprocessed Uranium |
| RMB | Renminbi |
| SASAC | State-Owned Asset Supervision and Administration Commission |
| SCWR | Supercritical Water-Cooled Reactor |
| SO₂ | Sulfur Dioxide |
| SOE | State-Owned Enterprise |
| SNPTC | State Nuclear Power Technology Corporation |
| SPC | China State Power Corporation |
| SPIC | State Power Investment Corporation |
| TRPO | Trialkyl Phosphate Oxides |
| UO₂ | Uranium Dioxide |

SUMMARY

China is on course to lead the world in the deployment of nuclear power technology by 2030. Should it succeed, China will assume global leadership in nuclear technology development, industrial capacity, and nuclear energy governance. The impacts will be strategic and broad, affecting nuclear safety, nuclear security, nonproliferation, energy production, international trade, and climate mitigation. Especially critical is whether China achieves an industrial-scale transition from current nuclear technologies to advanced systems led by fast neutron reactors that recycle large amounts of plutonium fuel.

CHINA'S ELECTRICITY POLICY CHALLENGES

After having consumed very little electricity for a century, China's 1.4 billion people consume more power today than any country in the world. Though per capita consumption is still only one-third of the West, China's appetite will keep increasing, driven by government policies favoring urbanization and cleaner appliances and vehicles. If future demand increases by half the historical rate since modernization, China's tremendous power consumption may double in two decades.

In response, China aims to diversify away from the coal firing that accounts for most of its electricity production. Beijing has pledged to clean the air in China's still-growing megacities by the 2030s and coal's ecological balance in China is woeful. Though China will pursue

many noncarbon options, Beijing sees nuclear energy as an important base load power source that is available, economic, and reliable.

UNCERTAINTIES FOR NUCLEAR POWER

China's nuclear power wager might not indefinitely pay high dividends. Until now, the state has boosted the nuclear power industry with incentives that, in the future, may come under pressure. The electric power system is subject to reform in the direction of more transparent oversight and pricing that might disadvantage nuclear investments. President Xi Jinping supports state control of strategic economic sectors, but he also advocates market reforms that have helped lead Western nuclear power industries into crises.

The nuclear sector must withstand what Xi calls "new normal" conditions: a gradual slowing down of China's economy, characterized by diminishing returns on capital goods investments and translating into rising debt and overcapacity. Nuclear investments may be affected by demographics, changes in electricity load profile, and technology innovations including emergence of a countrywide grid system able to wheel bulk power anywhere.

There is also political risk. Public support for nuclear power in China is volatile and may be low. Concerns since the Fukushima Daiichi accident in Japan have prompted Beijing not to proceed with long-established plans to build most of China's future nuclear plants on inland sites. Should this policy continue into the 2020s, prospects for China's nuclear construction sector will decline; indefinitely continuing nuclear construction at eastern coastal sites (where nearly all of China's nuclear power is generated) may encounter resistance on economic, capacity, and political grounds.

Under Xi, China's globalization continues but the state is assuming ever-greater liability. Political decisionmaking and corporate culture may not support an indefinite increase in the risk presented by more nuclear power investments. Some quasi-official projections before Fukushima that China by 2050 might have 400 or more nuclear power plants have been cut in half. Beijing's risk calculus may reflect that China's population would blame the Communist Party and the state for a severe nuclear accident. In a country with a patchy track record for industrial safety, said one Chinese planning expert in 2016, "The more reactors we have, the greater our liability."

OPPORTUNITIES AND RISKS IN ADVANCED TECHNOLOGIES

Until now, China's impressive nuclear development has relied on technologies invented a half-century ago by others and that China has replicated. During this century, China aims to replace light water nuclear power plants with advanced systems launched elsewhere but never compellingly deployed before.

- China today is poised to make these investments but lacks deep industrial expertise for some technologies it has selected; to succeed it must effect transitions from R&D to commercial deployment.
- China's current heavy nuclear R&D spending must be sustained to succeed since some systems may not be ready for commercial deployment before the 2030s.
- China's nuclear industry must depend on the state to make its nuclear technology transition; Beijing must down-select technologies and decide whether to trust the market to make economic decisions.

Whether China succeeds or fails, the global repercussions will be significant.

- If China merely replicates others' collective past experience, it will reinforce the view that fast reactors and their fuel cycles are too risky, complex, and expensive to generate large amounts of electricity.
- If, instead, China clearly succeeds in its ambitions, it may significantly raise the profile of nuclear power toward the twenty-second century.
- If so, China will deeply influence global rules and understandings governing the risks associated with nuclear power systems.

INTRODUCTION

The People's Republic of China is today the biggest platform in the world for the deployment of nuclear technology to generate electric power. In less than twenty years, China has increased its population of operating nuclear power reactors from three to thirty-eight, with eighteen more plants under construction. China currently accounts for more than half of the world's new nuclear power investment. In 2018, only the United States and France operate more nuclear power plants than China. According to current expectations, Chinese nuclear power production may surpass the United States, which has led the world in nuclear power generation for over half a century, sometime before 2030.

Following from China's success with nuclear power so far, external experts in government and industry generally anticipate that China will continue to successfully manage and move forward with its nuclear energy program in the coming decades. Especially in that case, decisionmaking in China's nuclear sector will likely significantly impact the global long-term outlook for nuclear power and the architecture of the nuclear fuel cycle; competition for nuclear exports; nuclear technology holders' strategic leverage over trading partners; and international nuclear governance.

Regardless of its future outcomes, China will profoundly influence what the rest of the world believes about nuclear power and the nuclear fuel cycle. China aims to transition from conventional nuclear power reactors to a fully closed nuclear fuel cycle based on fast breeder

reactors, spent fuel reprocessing, and the use of recycled plutonium fuel. If China fails, it will reinforce conventional thinking in some countries that nuclear fission is a transitional energy technology likely to be replaced this century by other sources. If China succeeds, prevailing low expectations for nuclear power may instead be dramatically revised. Other states may follow China's lead in projecting that nuclear power will be sustainable for centuries and that the risks associated with an industrial-scale "plutonium economy" are socially, economically, environmentally, and politically acceptable.

China's industry is poised to invade the world's nuclear goods markets. Continued Chinese success in nuclear power will add to the challenges faced by a nuclear industry in the West that is in deep trouble. Chinese state-owned enterprises (SOEs)—which were, until recently, expected to become "second tier" suppliers—may penetrate established nuclear power plant export markets. China's dirigiste business model may give its SOEs supreme competitive advantage over all foreign private sector companies in the nuclear industry. If Chinese business practices prevail, China might eventually become the world's leading provider of nuclear fuel, nuclear power plants, and nuclear engineering services.

Beijing will obtain strategic leverage where Chinese nuclear firms do business. Chinese success in exporting nuclear equipment, technology, and materials will open the road for China to replicate the success of the United States' Atoms for Peace program, in spreading its influence into the foreign, energy, and technology policies of China's nuclear partners and clients. The expense of spreading nuclear commerce, especially to developing countries, might be underwritten by China in support of its strategic interests.

The bigger China's nuclear power footprint grows, the more say China will have in global nuclear governance. If China in the coming decades becomes the leading nuclear power country, it will demand and obtain a commensurate role in members' decisionmaking concerning multilateral technical rulemaking compacts and organizations, including the Non-Proliferation Treaty (NPT), the International Atomic Energy Agency (IAEA), and the Nuclear Suppliers Group (NSG). If China closes the nuclear fuel cycle, global governance mechanisms related to nuclear security and nonproliferation may be adjusted to reflect that accomplishment.

While these developments loom on the horizon, the intensified buzzing of China's nuclear beehive has not escaped the attention of Chinese and international news media. However, the media's day-to-day focus on new contracts, nuclear industrial partnerships, reactor projects, and record-setting electric power production contribute to a misleading impression that China's nuclear power program will continue to expand indefinitely and incrementally without challenges, crises, or setbacks.

It is possible that, in the coming years, China's nuclear industry will not continue on the same robust trajectory as over the last three decades. That may even be likely should other

developments transpire, including: the widespread introduction of market reforms into China's electricity sector that would threaten government subsidies and assistance to the nuclear power industry; a prolonged economic slowdown combined with a deeper shift from capital investment to consumer goods; greater debt and globalization-fed risk aversion; the emergence of nuclear power input bottlenecks; and China's failure to make the transition from replicating established nuclear technologies to the more advanced, technically complex, and innovative systems that it wants to deploy in the future.

In any event, it would be a mistake to assume that China's nuclear program will continue on the course it has steered since the 1980s. China built up its nuclear power system under assumptions it made before embarking on profound reforms that tied China to the development of the global economy. Today, the consequences of these reforms—greater wealth, industrial corporatization, economic competition, more diversified growth, and rising expectations for environmental protection and political accountability—will constrain and influence the state's nuclear energy decisionmaking. To be successful, China's rulers will have to adjust longstanding nuclear policies and aims to take this evolution into account.

CHALLENGING THE WEST'S NUCLEAR INDUSTRY

The scale of China's nuclear energy industry alone ensures that how Chinese decisionmakers choose to manage this sector will have a great impact on the world's nuclear energy systems. By the end of the twentieth century, France's mature nuclear energy industry operated over fifty nuclear power reactors to supply about 80 percent of the electricity consumed by its population of 60 million people.¹ By contrast, when China connects its fiftieth nuclear power reactor to the grid, which is expected in a few years, China's nuclear power plants will contribute only about 5 percent of the electricity demanded by its population of 1.4 billion.²

Long before China set its sights on exporting nuclear power plants, the global nuclear industry had begun a process of consolidation that is still in progress. Since the 1980s, firms in Belgium, Germany, Italy, Japan, Netherlands, Sweden, Switzerland, the United Kingdom (UK), and the United States have abandoned the nuclear industry. Today, the nuclear engineering sectors of companies in France, Japan, and the United States, which supplied nearly three-quarters of the world's nuclear reactors, are in decline and their futures are uncertain. These firms are experiencing low-capacity utilization, rising costs, loss of expertise, and waning political support. Westinghouse Electric Company, a firm in the United States whose technology is the basis for over half the power reactors in the world, was selected by China in 2006 to provide the blueprint for a raft of its future nuclear power plants. In March 2017, after Westinghouse had transferred much technology to China and on the eve going forward with new business with China, the company filed for bankruptcy in the United States, saddled by nearly \$10 billion of debt resulting from cost overruns amounting to an estimated \$18 billion

for two nuclear plant construction projects.³ That followed revelations that Toshiba, a leading nuclear power vendor firm in Japan and Westinghouse's owner, would post a net loss of \$9.9 billion for 2016–2017.⁴ French firm Areva, Europe's leading nuclear vendor company, which has transferred nuclear power technology to China since the 1990s, recorded cumulative net losses of EUR 7.5 billion from 2014 through 2016.⁵

Should China's nuclear development remain on track, its industry's anticipated massive economies of scale and high turnover will also put foreign competitors under even greater commercial pressure. Under President Xi Jinping, the Chinese state has pushed forward with plans to further support and consolidate its SOEs, including companies in the nuclear industry that may be subject to megamergers. Wedding the might of Chinese industry to the central government's strategic and diplomatic aims, Beijing ordered its nuclear SOEs to collaborate to design Hualong-1, a national champion power reactor model that Chinese companies, at the behest of the state, are expected to aggressively export. In addition, Beijing planners are counting on exports of nuclear power plants to compensate for a marginal downturn in the domestic order books of equipment makers, engineering firms, and construction companies should demand for more reactors in China slow in the coming decades.

CHINA'S POLICY CHOICES AND STRATEGIC IMPLICATIONS

Ever since the mid-1980s, China has prioritized the development of nuclear power technologies because central planners considered them to be strategic. After a September 2016 address by Liu Baohua, the nuclear energy director of the China Atomic Energy Authority (CAEA), Chinese media summarized that nuclear power is “not simply an energy source” but is a technology with “other roles” in the Chinese state. Nuclear energy, they wrote, is “an important cornerstone of strategic power, a vehicle for civilian-military integration, and a ‘China card’ to play in the country's international cooperation diplomacy.”⁶

China views nuclear energy as strategic from several perspectives. The technology for nuclear power generation is derived from the same science and engineering pursuits that are the basis for the reactors, uranium enrichment plants, and spent fuel reprocessing plants used to produce nuclear weapons; indeed, the chain-reaction physics is the same for nuclear weapons and power reactors. A country with advanced nuclear fuel-processing technology for power reactors has the means to produce fissile material for nuclear explosives.

Skills developed and experience accumulated in a country's civilian nuclear energy applications can be put to use in its nuclear defense programs. The human and capital resources required for a successful nuclear energy program are great, and the timeline for nuclear power projects from conceptualization to decommissioning can be a century or more. Nuclear cooperation and the export of nuclear equipment, technology, and materials are vehicles for

states to access and influence other countries' decisionmaking on technology and energy. The greater a country's nuclear power infrastructure is, the more a country is able to influence global governance standards for nuclear safety, nuclear security, nuclear trade policy, and nuclear nonproliferation.

Finally, nuclear energy is expected to contribute significantly to China's intent to further urbanize its population by reducing air pollution in expanding megacities, and to show global leadership in reducing atmospheric carbon emissions. All of these strategic aims will factor into current and future Chinese decisionmaking about its nuclear power program.

From a strategic point of view, there are two reasons in coming decades why China's most significant nuclear power challenge will be the establishment of an industrial-scale fuel cycle. First, China has since the 1980s aimed to effect a transition from conventional power reactors to a nuclear system based on more advanced fuel cycle technologies, to ensure that nuclear power has a future extending beyond the twenty-first century. Second, the decisions China makes in this area will have profound impact elsewhere. Since the 1960s, efforts to establish a closed fuel cycle in France, Germany, Japan, the UK, and the United States have been shelved or terminated due in large part to public opinion, politics, and market forces. How these same factors will affect Chinese plans to deploy fast reactors and industrial-scale reprocessing plants is not yet known.

This report considers both internal and external factors that can be expected to contribute to Chinese nuclear energy policy making. In addition to overriding and long-term Chinese strategic interests, the most important internal drivers will be China's industrial policy concerning science and technology development, infrastructure investment, and electricity. The most important external drivers will be the forces of globalization. These could impact China's nuclear course in two ways: by exposing China's top-down and technocratic decisionmaking to increased influence from more Chinese stakeholders, and/or by encouraging and strengthening the impact of market forces in China's economy, including its electricity sector.

Decisionmaking on how China moves forward with nuclear energy development is complex and opaque. There are many actors and many interests. China has on several occasions reshuffled the organizations and hierarchies of its nuclear energy-related authorities and agencies. It can be anticipated that this bureaucratic evolution will continue toward mid-century, beginning with the preparation for China's next central planning milestones in 2020. Important decisions can be made with little regard for transparency. Indeed Chinese and foreigners have held different views about which Chinese government nuclear agencies are the most important.

So far, the decisions to select and deploy technologies for nuclear power generation have been made by the central government and the Communist Party of China without any significant

public input. In recent years, the Chinese public has paid increasing attention to government actions concerning welfare, equity, health, the environment, and safety, including in the nuclear energy sector. Public concerns have multiplied even as Beijing has strengthened nuclear safety oversight. In 2013 and 2016, Chinese authorities canceled plans to build nuclear fuel cycle installations in the immediate wake of local opposition. These cases may be harbingers of greater public intervention in nuclear matters, but it is not a foregone conclusion that the Chinese state will react to public pressure by overturning decisions to proceed with specific nuclear investments—especially if the government considers projects to be in the strategic national interest. Regardless of China’s growing interaction with the outside world, government decisionmaking under Xi has become more centralized, opaque, and unpredictable. His record should caution observers not to expect that a more globalized China will necessarily become more transparent or permit greater public participation in nuclear energy matters.

How China proceeds will likely be decided above all by the central government, as decisionmakers balance policy goals and the interests of actors and institutions, and assess risks and opportunities. This report examines the future of China’s nuclear power development through 2050 by considering both the policy choices and the strategic implications, domestic and global, which include China’s choice of advanced nuclear technology, policymaking in China’s electricity sector, management and assessment of nuclear project and political risk, as well as the prospect for Chinese nuclear exports and China’s nuclear governance.

This report is intended to serve as a vehicle for informing a growing number of stakeholders in China’s nuclear energy program, as well as a broader policy community outside China, about the background, influencing factors, possible outcomes, and significance of the decisions that China will have to make in the coming years. The report does not aspire to predict how China will make these decisions, nor who will make them, nor what the outcomes will be. The report is based on five years of research and information obtained in part from government planning documents, academic studies, financial reports from industry firms, records of conferences and meetings, and Chinese and foreign news media accounts. The report benefitted from uncounted discussions and interviews with government officials, industry executives, economists, scientists, consultants, lawyers, academicians, and civil society experts since 2011. The centerpiece of this project was three annual workshops with Chinese and foreign expert participants concerning the future of China’s nuclear energy program, held from 2014 to 2016 on behalf of the Carnegie Endowment for International Peace, in Beijing, Xiamen, and Berlin.

CHINA'S CHOICE FOR NUCLEAR POWER AND A CLOSED NUCLEAR FUEL CYCLE

THE STATE BRINGS NUCLEAR POWER TO CHINA

Throughout the thirty-five years that China has built up its nuclear power infrastructure, decisionmakers have been confident that nuclear power is consistent with and contributes to the realization of China's long-term aspirations and values. Ultimately, most critical decisions have been made by the leadership of the Chinese state and the Communist Party of China. Initiatives launched by hands-on actors—company executives, nuclear scientists, engineers, and planners—to significantly influence the direction of China's nuclear development have been translated into policy only after they were endorsed at the highest level of government.

China committed to generating electricity using nuclear fission energy with two significant steps. The first, taken in the late 1970s, was to launch initial nuclear power plant construction, and the second was to accelerate it in the mid-2000s. Both times, the country's supreme leadership took these decisions in consort with technocrats who promoted these actions with specific aims in mind.

China first began investigating nuclear energy during the 1950s, primarily on the basis of bilateral cooperation with the Soviet Union, which led to discussions in the mid-1950s about cooperation on an array of peaceful nuclear research projects including both magnetic fusion energy and fission reactors.⁷ The Chinese Academy of Sciences (CAS), founded on the Soviet model, included an Institute of Nuclear Physics that during the 1950s was engaged in

projects with both military and peaceful potential uses. By 1955, discussions on Sino-Soviet nuclear cooperation sidelined peaceful-use projects in favor of pursuing Chinese production of atomic weapons.⁸

Beginning in the 1950s, Mao Zedong gave China's military establishment a green light to develop atomic weapons and ensure, in his view, that China would not be blackmailed by nuclear-armed imperialist adversaries.⁹ China was by far the poorest and least developed of the states that developed nuclear arms in the years after World War II, and the military defeated advocates of nuclear power in bureaucratic battles waged over the allocation of China's limited resources for nuclear research and development.¹⁰

In 1964, after six years of dedicated work, China became the fifth country to build and successfully detonate a nuclear explosive device, following the United States (1945), the Soviet Union (1949), the UK (1952), and France (1960). Of these states, all but China quickly followed up their nuclear explosive tests with the construction and operation of nuclear fission reactors to generate heat that could be transformed into electric power.

For a decade beginning shortly after China's first nuclear explosive test, domestic turmoil unleashed by Mao's Cultural Revolution sidetracked any efforts to establish a nuclear power program.¹¹ China approved the construction of its first nuclear power station only in 1981—eighteen years after France, the last of the first four nuclear-armed states, had begun producing nuclear electricity.¹²

The road to nuclear power in China was cleared after modernizers and reformers, who had emerged in the Communist Party during the 1970s, took control of the state by the end of the decade. Chinese scientists and electric power technocrats convinced Deng Xiaoping, Zhao Enlai, and other leaders that nuclear power would reduce China's dependence on polluting coal, boost electricity output in densely populated coastal areas, and permit China to catch up with foreign countries that were far ahead in nuclear technology.¹³ Encouraged by this thinking, Chinese SOEs backed by provincial and local governments built a handful of nuclear power stations with help from foreign industry partners during the 1980s and 1990s.

In 2005, China dramatically magnified its nuclear construction program. As with the initial decision to build power reactors a quarter-century earlier, leaders and technocrats were in agreement. This time, then premier Wen Jiabao shared experts' view that nuclear energy production should be greatly accelerated and that a nuclear power renaissance was about to take off in advanced countries. Behind the scenes, China's central planners increasingly advocated nuclear power as an answer to the problems of energy security and pollution that had been unleashed by China's economic growth.

In March 2005, Wen adjusted the government's policy on China's level of nuclear development from "appropriate" to "energetic." This decision of principle was promptly incorporated into the fine print of China's Eleventh Five-Year Plan for 2006 to 2010 and then into a newly conceived Medium- and Long-Term Plan for Nuclear Power Development for 2005 to 2020.¹⁴ China set the target of expanding nuclear power generation capacity from seven gigawatts (GWe), achieved in 2005, to 70 GWe in 2020.¹⁵ French, Russian, and U.S. firms were encouraged to compete with each other for the prize of providing the technological blueprint for a series of future nuclear power plants in China. Beijing selected Westinghouse Electric Company and, in 2006, gave the State Nuclear Power Technology Corporation (SNPTC)—a company set up by the State Council of Ministers, the chief administrative authority of China's central government, to take charge of foreign nuclear power plant technology—approval to sign a contract with Westinghouse for the first four units. In parallel, the leadership of the China National Nuclear Corporation (CNNC), the most important nuclear SOE, prepared to build as many as thirty reactors under the government's expanding nuclear horizons.

During the two decades between the launch of China's first nuclear power plant projects and its decisions to accelerate nuclear development, the successive Chinese premiership transitions from Li Peng to Zhu Rongji and then to Wen Jiabao underscored how essential it was that support from the top leadership match technocrats' advocacy of nuclear power. Li became premier in 1988 after a long career as an electricity manager and vice minister for power, and he unflinchingly championed nuclear energy projects. Zhu, who succeeded Li in 1998, did not share Li's enthusiasm for nuclear energy. Zhu instead shifted new investment away from nuclear projects and he favored building up China's petroleum sector and making electric grid improvements. At the end of the 1990s, he imposed a three-year moratorium on power plant construction. In 2003, Wen Jiabao succeeded Zhu and reversed Zhu's policies on atomic energy. Wen revved up nuclear power plant building, having been convinced by nuclear advocates in the planning and science bureaucracies that this was necessary to put an end to crippling coal transport bottlenecks that led to electricity shortages.¹⁶ Wen's decisions in the mid-2000s were in some quarters criticized as an overreaction to short-term events, but they initiated a crash program to rapidly build up China's nuclear power infrastructure.

China's top leadership once again directly intervened in the country's nuclear development six years later, after the severe accident at the Fukushima Daiichi nuclear power plant in Japan in March 2011. This marked the first time that China made decisions about its nuclear program in reaction to external nuclear developments. China's rulers were not prepared for the self-inflicted destruction of three reactors in Japan. With two dozen reactors operating or under construction in China, the leadership promptly ordered technocrats to take the necessary steps to ensure that a similar accident would not happen.¹⁷

Five days after the accident in Japan, the State Council of Ministers suspended approvals of new nuclear power projects in China and postponed construction of a number of previously approved nuclear power stations. In October 2012, following an internal government debate about nuclear safety that spilled over into the more visible National People's Congress, China officially proclaimed that construction of nuclear power plants at inland sites—an essential element in China's plan since the mid-2000s to greatly expand nuclear power beyond China's crowded coastal perimeter—would be suspended until 2015.

As of 2018, the Fukushima accident has not affected the overall direction of Chinese policy but it nearly immediately precipitated a more conservative approach by the government toward project approval. According to a former Western government official who at the time conferred with Chinese counterparts, the Japanese disaster initially prompted China's leadership to seriously consider, but ultimately decide against, reversing the course set by Wen in 2005 to build up China's nuclear power capacity.¹⁸ In the end, the leadership's response to the accident was a compromise: Beijing halted construction of reactors based on older technology and ordained that only projects featuring new reactor models would be approved. As a result of these decisions, nuclear power plant construction targets for the Thirteenth Five-Year Plan (2016–2020) might not be met on time.

Should plans to build nuclear power plants on inland sites be restored in the Fourteenth Five-Year Plan, China's nuclear power program may remain on track to cross the 100-reactor threshold sometime during the 2020s. But in the meantime, the State Council's 2011 decision to selectively suspend nuclear construction and probe the safety of all of China's nuclear power plants has provided political cover for some officials in central government ministries and industry to assert more openly than at any time since 2005 that the ambitious pace is too risky and should be slowed down.¹⁹ As of 2018, the government had reached no consensus about how many more nuclear power plants China will build in the coming decades. Chinese government agencies, research and development (R&D) organizations, and their consultants project capacity figures for 2050 in a broad range between 150 GWe and 500 GWe. Projections made before Fukushima were more frequently in the 400–500 GWe range. Some projections made after the accident are considerably lower, between 150–250 GWe.

STEADFAST NUCLEAR POLICY COMPONENTS

From the outset, Beijing aimed to establish a stable organizational structure and hierarchy for its nuclear power activities. Over four decades, the central government has called into being, rearranged, and in some cases dissolved a panoply of ministries, commissions, agencies, inter-agency “leading groups,” and SOEs in an effort to juggle the competing interests of various actors including academic research institutions, nuclear weapons scientists, the military, the mining sector, the power industry, state government central planners, and the Communist Party.

Currently, the State Council of Ministers is the most important authority responsible for making decisions concerning the future direction of nuclear power in China—but its subsidiary agencies have very different interests. During the last two decades, the state has created a number of bodies responsible for nuclear power decisionmaking under the State Council. These include the National Energy Administration (NEA), which is responsible for policy implementation and represents a score of government bodies and departments; the National Development and Reform Commission (NDRC), responsible for planning and infrastructure development; and the National Nuclear Safety Administration (NNSA), which is China’s nuclear power regulatory body. It began as a politically weak department of China’s Ministry of Environmental Protection and has been elevated in status over the last decade. Since 2010, policymaking has been coordinated by a National Energy Commission representing over twenty government departments.

China’s nuclear bureaucratic structure for many years has been sufficiently opaque that foreign governments and Chinese officials involved could not even agree which agencies were in charge. According to one researcher, Western observers were misled for over two decades to believe that nuclear energy policy is largely determined by CAEA. Over time, it claimed for itself numerous policy-related functions. “In practice, none of these functions or categories of work are taken by or carried out by CAEA, except when representing China at the IAEA.”²⁰

Independent of how Beijing arranges and rearranges its official nuclear energy competencies, several overarching energy policy aims with strategic significance have consistently figured in China’s decisions concerning nuclear power development: to assure that a growing China would have sufficient energy; to diversify and more efficiently manage China’s energy fuel resources; to centrally control the process and direction of industrial application of technology; and to reduce atmospheric pollution by reducing the consumption of coal for electricity production.

REGIONAL DEVELOPMENT AND FUELS DIVERSIFICATION

From the outset, a continuous thread in Chinese nuclear energy planning has been the aim to reduce China’s reliance on burning coal for electricity production and to redress imbalances in the distribution of the country’s energy resources.

China has over 10 percent of the world’s coal reserves but very few other fossil fuel resources, and for many decades it has generated a huge share of its electricity by burning coal.²¹ Nearly three-quarters of China’s coal reserves are in the country’s north and northwest, far from the electricity load centers on China’s eastern seaboard. Between 1975 and 2000, the share of electric power that was generated by China’s coal-fired plants steadily rose from 56 percent to 78 percent.²² Anticipating this trend at the outset of modernization, Chinese nuclear scientists argued that using nuclear energy might mitigate difficulties in transporting ever-greater amounts of coal from China’s interior to urbanizing coastal areas. Zhou Enlai, who was an

early convert to this vision, said in February 1970 that, “from a long-term point of view, nuclear power is the only solution for the shortage of electricity in Shanghai and East China.”²³

Zhou’s remarks were prompted by an acute power shortage in Shanghai. Thirty-five years later, another power crisis on China’s seaboard, likewise triggered by inadequate coal supply, encouraged then premier Wen to ramp up nuclear construction. Wen was pressed hard by a key figure, then vice premier Zeng Peiyan, who was convinced that shortages would get worse unless measures were taken to strengthen electricity production not based on coal. That logic implied that China would have to expand both nuclear power and hydroelectric power. Zeng, supported by the nuclear power industry, argued that a nuclear power expansion for the east coast was necessary because most of China’s coal resources were in the north and most hydropower sources were in the southwest, so it took half of China’s rail transport capacity and one third of its river transport capacity to supply seaboard cities with coal to be burned for electricity production.²⁴

TECHNOLOGY AND INDUSTRIAL POLICY

At the same time, China’s leadership was wary of political risks associated with unbridled nuclear power development. During the late 1970s and beyond, Chinese policymakers debated whether China should develop its nuclear power infrastructure on the basis of indigenous capabilities—implying that progress would take longer—or instead rely on fast-track cooperation from foreign governments and industries that already commanded the essential technologies and expertise that China sought. Advocates of home grown development included experts from China’s nuclear weapons program who sought to expand into profitable industrial projects. They also felt betrayed by the Soviet Union’s decision to not provide China with a nuclear weapon design in 1959.²⁵ Ultimately, China embarked on a compromise two-track plan in the 1980s that attempted to reap the benefits of foreign technology transfer but also protect the interests of China’s industry.

This dual-track approach also informed the establishment of what would become China’s two most important nuclear SOEs. The first, CNNC, was hived off from Beijing’s former nuclear industry ministry in 1988. CNNC was critical of foreign influence in China’s nuclear development and was selected to spearhead nuclear power plant construction in the Shanghai region. The second firm, China General Nuclear Power Holding Company Limited (CGNPC), was formed in 1994 on orders from Beijing policymakers expressly to facilitate nuclear power development with foreign companies—particularly with French industry—as a counterweight to CNNC.

CGNPC set up a nuclear power plant at the Daya Bay site in Guangdong based on French technology. During this project and immediately after, managers and politicians in Guangdong aimed to expand nuclear construction with French industry to sustain rapidly growing

wealth and electric power demand in southeast China. During the 1990s, their efforts were deflected by suspicious central government officials in Beijing; they were concerned that the decisionmaking freedom secured by Hong Kong as a condition of the UK's 1997 handover to China would spread to adjacent Guangdong.²⁶ These foreign-indigenous and center-periphery tensions and debates inhibited China's nuclear development throughout the 1990s.

By the end of the century, China's central government had resolved these issues to its satisfaction. Beijing was thereafter willing to assume the residual risk that more nuclear power plant construction in Guangdong and elsewhere might empower increasingly wealthy and globalized actors to wrest autonomy from or destabilize the central government. In parallel with decisions in the early 2000s that opened China's nuclear power sector to greater foreign participation, the central government ruled that decisions on making investments in electricity production must be approved by Beijing. Further, the central government presided over an ongoing restructuring of China's nuclear power industrial sector, which in practice assured that CNNC and its subsidiaries would own shares in virtually all important companies (including rival CGNPC) that were being set up to serve an increasingly technologically deep and geographically broad Chinese nuclear industry sector.²⁷

Since the beginning of its nuclear power program, China's leaders have made sure that, through SOEs, the central government firmly controls the future direction of nuclear power development, even if the details were left to company executives whose interests might differ. The State Council's establishment of CNNC and then CGNPC was part of a more general process of reorganizing strategic economic activities under its control; it broke up former defense industry ministries and established SOEs responsible for aviation, aerospace, arms production, shipbuilding, and nuclear energy. In setting up its first nuclear SOE, the State Council tasked CNNC to construct and design nuclear power plants; produce nuclear fuel, isotopes, and military nuclear hardware; and manage nuclear waste. As the nuclear program expanded, the state created more SOEs in the 1990s, including CGNPC.

The State Council's decisions set in motion a process of corporatization that in some areas has profoundly altered the relationship between the state and China's nuclear industry. China's leaders had intended to decentralize, "civilianize," and render profitable China's military-industrial complex. In fact, their decisions had the unintended consequence of setting up a contradiction between the state's intent to open China's economy to competition while maintaining firm political control over key strategic sectors. Whereas the state aimed to protect its interests in the companies it set up, bargaining relationships formed and persisted "between the state enterprises and their bureaucratic superiors."²⁸ As time progressed, nuclear firms eventually established parallel decisionmaking structures, and the companies formed relationships with local and provincial governments that had been freed by reforms from Beijing's tight grip. These developments encouraged nuclear SOEs to develop their

own unique interests that were distinct from the state's, aimed at limiting financial accountability and oversight and promoting overemployment and protectionism.²⁹

Beginning in 1985, the project to set up a small cluster of nuclear power reactors in Guangdong committed French industry to contribute to China's aggressive localization drive for nuclear power plant construction, equipment manufacture, and operations. In addition, the French side carried out an extensive workforce development program to prepare CGNPC to take over all aspects of the management of nuclear power stations in Guangdong.³⁰ Similar agreements were pressed upon partners in the United States to transfer the technology for Westinghouse-design power reactors to China. More limited localization agreements with similar workforce development programs were forged with partners in Russia and Canada.

Over the course of twenty years, Chinese policy on nuclear technology choice followed most other nuclear power-generating countries by focusing nearly exclusively on light water reactors (LWRs), which were considered the safest bet and in line with international trends. By the mid-2000s, safety concerns about the 400 LWRs operating in the world were diminishing as these units amassed operating experience. China accordingly prioritized obtaining independent intellectual property for this technology.

ELECTRICITY AND GROWTH

China's decision to greatly accelerate nuclear power plant construction in the mid-2000s was prompted in part by broader energy security concerns. Planners remained convinced that China's capital investment-led growth model would continue to assure high economic growth, provided it was underpinned by a commensurate and increasing supply of base load electricity.

The severe wintertime coal and power shortages on the east coast, which in the 1970s had propelled China's first nuclear investments, prompted leaders in the early 2000s to overreact. Inside of a year after decisions were made to ramp up, central planners were predicting that China would instead soon face a power surplus.³¹ However, the leadership, true to form, dismissed the surplus as a short-term adjustment and remained confident that the economy—and with it electricity demand—would continue to expand as it had during the last decade. In 1996, then premier Li told the National People's Congress that China's 1980 expectation that gross domestic product (GDP) would quadruple by 2000 had been "fulfilled five years ahead of schedule."³² The next planning targets, in China's Tenth Five-Year Plan (2001–2005), were accordingly based on expected annual GDP growth of 7 percent, and the Eleventh Five-Year Plan (2006–2011) predicted GDP growth of 9 percent. Both goals were, in fact, exceeded.

With continued high economic growth putting China's energy resources under strain, planners aimed to reduce China's overall energy intensity of GDP—the Eleventh Five-Year Plan

called for a reduction in energy intensity by 20 percent. But they cautiously anticipated that, as the Chinese got richer and continued to urbanize, the *electricity* intensity of GDP would comparatively decline far less. Economists employed by China's power sector expected a long-term close correlation between electricity consumption, urbanization, and GDP, as has been the historical experience of Western industrial economies.³³

Chinese data substantiated this expectation. The percentage of China's urban population rose from 19 percent in 1980, to 36 percent in 2000, to 56 percent in 2015. China's per capita consumption of electricity during the same period rose from 281 kilowatt-hours (KWh) in 1980, to 993 KWh in 2000, to about 4,000 KWh in 2015.³⁴ During China's first two nuclear power decades, growth in Chinese electricity demand very closely matched growth in GDP. By 1995, China overtook the United States as the world's biggest consumer of electric power. During most of the period following Deng's reform initiative, China recorded an annual increase in power consumption of about 10 percent. Between 1980 and 2014, Chinese industry actually increased the country's electricity generating capacity twenty-three-fold, from 60 GWe to 1,360 GWe, an average annual increase of 9 percent.³⁵

China's aggressive nuclear expansion in 2005 should be viewed considering growth, demographics, and energy fuel security. Inside the government, technocrats who were convinced that China would need more nuclear power worked to prevent more cautious planners at the NDRC from derailing Wen's "energetic" nuclear development. In 2008, technocrats who strongly believed that China needed a dedicated central government agency to strategically evaluate and coordinate the nation's energy policies created a National Energy Administration (NEA) staffed at first with fewer than 100 people. According to government sources in China, while initially NEA was not endowed with any real authority, it has since assumed from NDRC the task of outlining future electricity planning targets. Today, NDRC generally follows what NEA proposes.³⁶

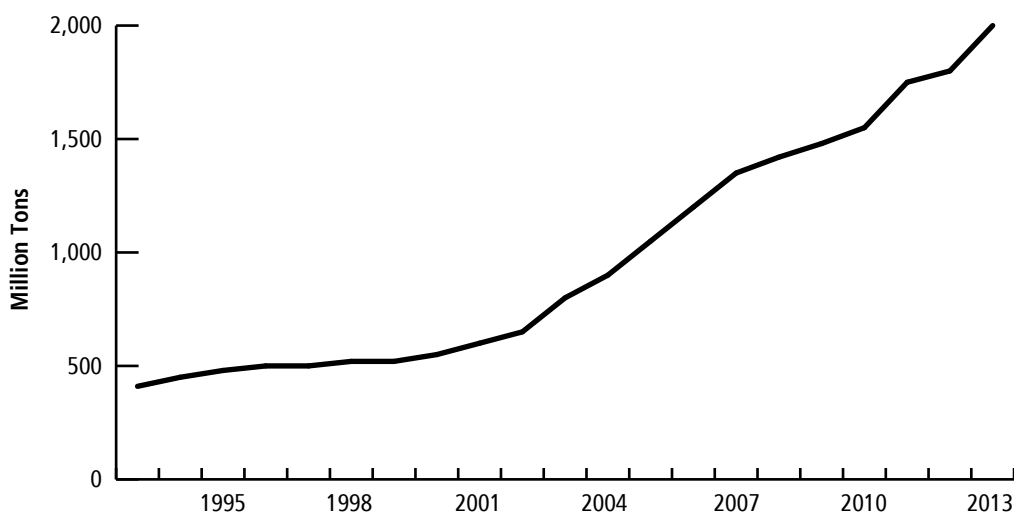
ENVIRONMENTAL POLICY

Modernizers who advocated nuclear energy beginning in the 1970s argued that nuclear power, unlike coal, would not pollute the air. In deciding to accelerate China's nuclear program, technocrats and the political leadership agreed that nuclear power would marginally reduce growing levels of particulates emitted by coal-fired power plants that were polluting China's air as a consequence of uninhibited economic growth. Over the ensuing twenty years, China's leaders demonstrated greater concern about increasing pollution levels and then gradually followed the trend of promoting global awareness of the threat of greenhouse gas emissions. China refrained from committing to reducing carbon emissions during negotiations of the 1999 Kyoto Protocol. But five years later, China singled out nuclear power as a carbon-free energy source worthy of greater investment in the 2004 Medium- and Long-Term Planning Outline for Energy Development, permitting future nuclear technology "leapfrogging."³⁷

Nuclear power advocates who aimed to fight coal-fired emissions argued that many more nuclear power plants would be required to make a difference. They were right. Through China's first three nuclear power decades, reactors accounted for less than 3 percent of China's consumption of electricity fuels. Even after nuclear power deployment was accelerated, China has continued to build many coal-fired power stations. In just five years—between 2005 and 2009—China added coal-fired power generating capacity equivalent to the total coal-fired capacity in the United States. Between 2010 and 2013, China added another 50 percent of the total U.S. capacity.³⁸ Currently, China burns about four billion tons of coal per year, and for many years will continue to burn tremendous amounts. After fifteen years of forced nuclear power reactor construction and renewable energy technology deployment, the reality is that burning coal will still account for two-thirds of China's electricity production in 2020.³⁹

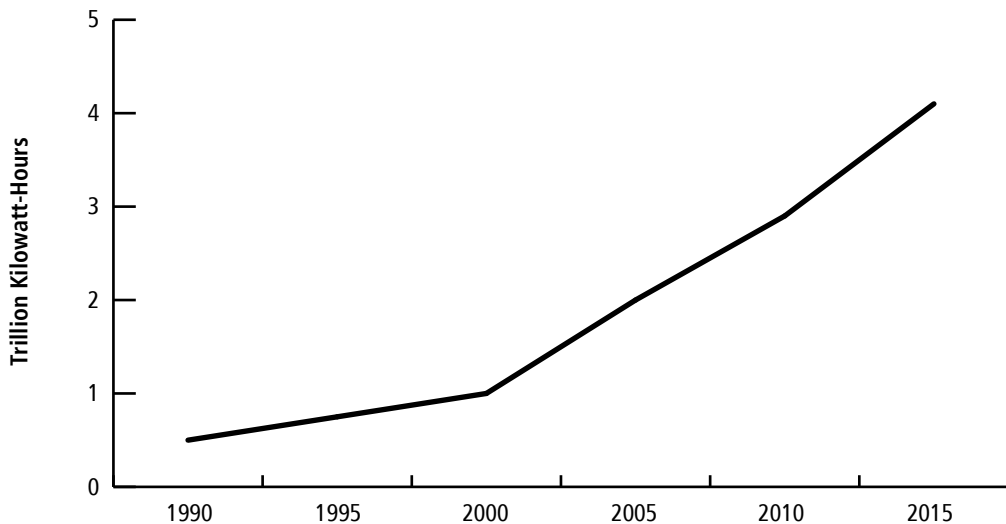
In the five-year period before the 2005 decision to speed up nuclear development, coal burning in China had increased by 75 percent, which contributed to China's failure to meet ten of thirteen pollution control targets for its Tenth Five-Year Plan (2000–2005). China was, by then, the biggest emitter of atmospheric sulfur dioxide (SO₂) in the world. In 2005, China exceeded the emissions ceilings for SO₂ and soot set at the beginning of the plan by, respectively, 42 percent and 11 percent. World Bank data published a year later shows that, by 2005, atmospheric particulate levels in Chinese cities were four times higher than in comparative metropolitan areas in North America and Western Europe.⁴⁰

CHINA COAL CONSUMPTION FOR THERMAL POWER GENERATION



Source: U.S. Energy Information Agency (EIA)

CHINA ANNUAL COAL-FIRED ELECTRICITY GENERATION



Source: U.S. Energy Information Agency (EIA)

CHINA'S NUCLEAR FUEL CYCLE

Beginning in the 1980s, in addition to building nuclear power reactors, China made preliminary decisions about what to do with the used fuel and waste that its nuclear power plants would generate. From the outset, China mirrored foreign nuclear programs' visionary considerations about energy resource management and technological development.

Currently, all the reactors China has built for power generation—like nearly all power reactors worldwide—are so-called thermal reactors that use neutrons that are slowed by a moderator, usually water, in the core of the reactor. Nearly all of these thermal power reactors are LWRs, and all of China's LWRs are pressurized water reactors (PWRs), the most common type of LWR. Slowing down the neutrons in these reactors increases the likelihood that their collisions with nuclei in the core will result in fission reactions that produce heat, radioactive fission products, and a number of heavy, transuranic elements. The heat is harnessed to produce steam that drives an electric generator. When the concentration of chain-reacting isotopes in the fuel becomes depleted during reactor operation, the highly irradiated (or spent) fuel assemblies, containing the fission products and transuranic matter, are removed from the reactor core and placed into pools filled with water, where the fuel assemblies lose residual heat and radiation levels gradually decrease. When the spent fuel is removed, it is very hot and intensely radioactive, requiring active cooling for several years after it is taken out of the reactor.

Like other countries, China has two basic options for managing its spent fuel from these reactors. China may store the spent fuel indefinitely in water-filled pools and/or in air-cooled dry casks, either at the reactor site where pools are located or at a centralized storage facility serving a number of nuclear power stations. Eventually, the spent fuel must be disposed of in an underground geological repository. Alternatively, China may remove some or all of the spent fuel from storage after a few years and bring it to a reprocessing plant, where the fuel is broken up and dissolved, and various components—uranium, plutonium, other transuranic elements and fission products—are separated and recovered. The plutonium and uranium may then be used to make new fuel. All other materials from the reprocessed spent fuel are collected, stored, and disposed of as waste in a geological repository.

Worldwide, currently about 300,000 metric tons of heavy metal (MTHM) of power reactor spent fuel is being stored, mostly at reactor sites, from over 400 power reactors that have operated since the 1950s.⁴¹ About 90 percent of this spent fuel is stored in water-filled pools and the rest in dry casks. Every year, the world's power reactors add about 12,000 MTHM to the world's spent fuel inventory. By 2030, an additional 400,000 MTHM in spent fuel may be generated.⁴²

A small fraction of this spent fuel is annually reprocessed; in the recent past, as much as about 3,000 MTHM per year, but the amount is currently less.⁴³ The reprocessing of power reactor spent fuel involves chopping up the fuel assemblies to expose the uranium dioxide (UO₂) fuel matrix. The fuel is then dissolved in hot nitric acid. The dissolved components of the fuel are then separated from the undissolved residue of fuel cladding and some waste fission products. The dissolved fuel is contacted with organic solutions to separate the nuclear materials. Ideally, these materials, particularly the uranium and plutonium, are recovered. The residual wastes are separately concentrated and mixed with a solid medium, such as vitrified glass, and stored until they can be permanently disposed of in a geological repository. The recovered uranium and plutonium can be recycled as reactor fuel.

In a few countries, led by France, recycling nuclear materials from spent power reactor fuel is a mature industrial activity. During a period of more than twenty years, France has reprocessed over 26,000 MTHM of spent UO₂ fuel. The plutonium extracted from this spent fuel has been combined with uranium and recycled as mixed oxide (MOX) fuel in twenty-two French LWRs and forty reactors worldwide, resulting in natural uranium savings of about 17 percent.⁴⁴

In the majority of countries, governments and industries launched nuclear power programs without initiating specific investments or concrete actions concerning the long-term management of their spent fuel. China was no exception. Beijing, during the late 1970s, looked forward toward the construction of its first nuclear power plant without a plan for managing its spent fuel beyond storing it at the reactor site. For several decades, spent fuel from China's

growing number of power reactors has been stored in water-filled pools located at the plant sites.

When China's first nuclear power plants were still on the drawing board, the leadership in Beijing was only dimly aware that the discharged spent fuel must be carefully managed for hundreds or thousands of years. By the mid-1980s, as reforms continued unabated under Deng Xiaoping, that situation had considerably changed. Leading technocrats—the most important of whom had been part of China's nuclear weapons development drive a generation before—had convinced the leadership that nuclear energy technology was critical to China's long-term future. Beyond the program approved by Deng to build a few power plants equipped with PWRs, these officials crafted a visionary narrative: fast breeder reactors, fueled with plutonium recovered by reprocessing China's expanding inventory of spent fuel, would provide a potentially unlimited source of energy.

REPROCESSING

In 1986, Deng, supported by leading scientists and technocrats from China's strategic weapons programs, established the National Program for High Technology Development, the so-called 863 Program, to accelerate China's technological development.⁴⁵ This R&D program financed pilot projects for what was then called “reprocessing for the thorium-uranium fuel cycle” and for development of a fast neutron reactor.⁴⁶ These two projects emerged as cornerstones of China's ambition to establish a closed fuel cycle.

In 1987, in tandem with preparations for the construction of China's first two nuclear power plants—the Qinshan-1 station in Zhejiang Province and the two-reactor Daya Bay station in Guangdong Province—Beijing made known that China, like Japan, Russia, and other leading nuclear power countries, would reprocess rather than dispose of its spent fuel, recover the plutonium and uranium, and use these nuclear materials as fuel for reactors. The Bureau of Nuclear Fuel in China's Ministry for Nuclear Energy informed the IAEA that China would begin by setting up a pilot reprocessing plant by the mid-1990s, followed by an industrial-scale reprocessing plant by the early 2000s, to accommodate spent fuel from Qinshan, Daya Bay, and future Chinese nuclear power plants. Before reprocessing, spent fuel from China's east coast nuclear power stations would be stored in water-filled pools at nuclear power plant sites for between three and five years. After, the spent fuel would be shipped to a central storage site in “northwest China,” where the spent fuel would be reprocessed in the pilot plant.⁴⁷

China's plans to set up reprocessing plants closely tracked with advanced nuclear countries' rationales. All professed that, in the long term, fresh uranium fuel would become expensive and that reprocessing would ultimately lead to safer nuclear waste management, thanks to new techniques for partitioning and separation of radioactive isotopes that would limit the amount of nuclear waste and permit maximum recycling of nuclear materials. Accordingly,

officials from the Ministry of Nuclear Energy told the IAEA that China would reprocess its spent fuel for four reasons: 1) to recover uranium and plutonium from spent fuel and use it for nuclear fuel (without reprocessing, “nuclear resources are not utilized in full”); 2) because of high costs for uranium mining, processing, and enrichment in China; 3) because “the ultimate disposal of high-level vitrified [radioactive] wastes is safer”; and 4) to take advantage of the future recovery of other transuranic elements, including neptunium, americium, curium, “and some valuable fission products such as palladium and rhodium, from reprocessing effluents to meet various needs.”⁴⁸

China proceeded with the design and construction of its pilot reprocessing plant, completing and, according to Chinese experts, successfully commissioning it in December 2010—fifteen years later than originally foreseen in the 1980s. Stepwise commissioning of the installation, set up at the military Plant 404 site at Jiuquan in Gansu Province in remote western China, began in 2004 and took seven years. Some delays were administrative, while others were due to difficult cooperation with Russian counterparts after the collapse of the Soviet Union and by quality control issues experienced during plant construction.⁴⁹ Officials at the China Institute of Atomic Energy (CIAE), an R&D institution that since the 1950s had been a leader in China’s nuclear materials science, predicted in 2005 that Wen’s decision to accelerate nuclear power plant construction would delay fuel cycle development further because China would prioritize ongoing PWR-based power plant construction instead.⁵⁰ Chinese experts said after commissioning of the reprocessing plant that the project had benefited from twenty years of R&D experience and China’s successful operation of three reprocessing plants that were built in the late 1950s to separate plutonium for China’s nuclear weapons program and operated until decommissioning in the 1980s.⁵¹

Over two decades, the pilot plant project served as a test bed for certain technical innovations that went beyond the 1950s-vintage technology of China’s decommissioned military reprocessing plants. Beginning in 2004, the pilot plant demonstrated a Chinese-designed bundle shear used to chop the spent fuel. It also tested the process chemistry equipment used to dissolve the spent fuel; it controlled key parameters such as pressure, temperature, feed rates, and separation speed, including by centrifugation; it calculated accounting mass balances for the nuclear materials in the system; it tested the behavior of process chemical equipment for separation; and it measured the rates of plutonium and uranium recovery, decontamination, and purification.⁵²

Some technologies chosen for solvent extraction and purification technology in the pilot plant were different than what had been used in China’s military reprocessing plants. As intended, China has used the plant to develop experience in design and construction of reprocessing installations, train operations personnel, and recover highly enriched uranium from spent fuel irradiated in Chinese materials testing reactors (MTR), as well as recover materials intended

for use in future power reactors. According to Chinese experts, the Ministry for Nuclear Energy projected a quarter century earlier that these activities should be carried out in the pilot plant soon after it was commissioned.⁵³

Open-source data suggest that the pilot reprocessing plant was originally conceived to separate at least several tons of plutonium to be used as nuclear fuel during its lifetime operation. The plant's design, for example, included a head end featuring a pool storage area to accommodate 500 MTHM in spent LWR fuel and 50 MTHM in spent MTR fuel, from versatile high-power research reactors.⁵⁴ Most nonofficial sources estimate the design throughput of this plant as 50 MTHM per year, consistent with the dimension of the spent fuel storage area under the assumption that the plant would routinely operate to recover plutonium and uranium.⁵⁵ However, at some point during its initial operation phase, the pilot plant was no longer intended to routinely or continually generate recovered nuclear fuel materials. In early 2016, a Chinese scientist close to the project said that 50 MTHM would be the maximum amount of spent fuel reprocessed over the plant's entire lifetime. Other experts said later that year and in 2017 that the cumulative lifetime throughput of the plant will probably be far less than 50 MTHM, perhaps even a small fraction of that amount, depending on whether the plant would be modified. If so, some upgrades would be intended to address unusually high measurement uncertainties for the plant's nuclear material inventory, attributed to a combination of measuring and process engineering issues.⁵⁶ These statements from Chinese experts are consistent with data reported annually by China to the IAEA on the status of its civilian plutonium inventory, suggesting that the pilot plant has operated infrequently, that very little spent fuel has been reprocessed, and that operation may have been indefinitely halted in 2014.⁵⁷

FAST NEUTRON REACTORS

In 1987, the Ministry for Nuclear Energy reported to the IAEA that an important objective of the pilot reprocessing plant would be to recover plutonium to be made into fuel containing both plutonium and uranium—so-called mixed-oxide or MOX fuel—for future fast breeder reactors.⁵⁸

China's LWRs are fueled with low-enriched uranium and use water to cool the fuel and slow down (or moderate) the neutrons emitted by the fuel in the core of the reactor to increase the probability that they will cause exothermic fission reactions. Fast reactors do not use water or another substance to moderate the neutrons and so these remain high-energy, or "fast," neutrons. To use fast neutrons, these reactors need fuel with a higher content of fissile material, either highly enriched uranium or plutonium. If the fuel in the core is surrounded by a "blanket" made of the isotope uranium-238, that so-called depleted uranium can capture fast neutrons emitted by the fuel, and the uranium-238 will be converted to plutonium-239. In

this way, a fast neutron reactor can be operated to “breed” large amounts of plutonium that, in turn, can be used as fuel for more fast breeder reactors. Most of the world’s fast reactors have been cooled with liquid sodium, which efficiently transfers the heat generated by fission energy to a turbine-generator system to produce electric power.

China’s resolve to set up fast breeder reactors also tracked decisions that had previously been taken by advanced nuclear power countries beginning in the 1950s. By the time China initiated construction on its first LWRs in the late 1980s, France, Germany, India, the Soviet Union, the UK, and the United States had all embarked on ambitious fast breeder reactor development and construction projects meant to point the way toward a future transition from LWRs to more advanced, complex technologies. Several of these countries had in parallel prepared for the production of MOX fuel for future fast reactors.

Hand in hand with the central government’s 1986 approval of the pilot reprocessing project under the 863 Program, China simultaneously embarked on a project for a pilot fast breeder reactor.

During the 1960s, Chinese researchers interested in fast reactors set up a sodium circuit test loop, a mock-up of a fast reactor circuit that contains hot liquid sodium, and constructed a zero-power installation using uranium. It reached criticality in June 1970, despite political turmoil brewing in China. In the 1970s, technocrats from China’s defense nuclear program persuaded Deng and other leaders that, together with reprocessing, the breeder reactor was justified because the supply of uranium was limited and the cost of processing uranium was high. The same arguments had been put forth by breeder reactor advocates in other countries, under the assumption that nuclear power generation would rapidly expand worldwide and that the United States would establish a uranium cartel to control access to the world’s nuclear fuel supply.

To enhance their claim that nuclear energy belonged in the suite of technologies deemed strategic for China and hence qualified for support under the 863 Program, nuclear scientists mapped out a three-stage, long-term vision for the development of nuclear technology. They forecast that China’s (and the world’s) current LWR-based nuclear power infrastructure would be succeeded by fast breeders fueled by recovered plutonium and uranium, and that this nuclear power system would in turn be succeeded by a still-more-advanced system based on nuclear fusion energy.⁵⁹ Similar visions had been put forth by breeder reactor advocates in other countries, notably India.⁶⁰

In 1986, China included the fast reactor in the 863 Program and built about twenty experimental sodium loops, including two imported from an abandoned fast reactor program in Italy. CIAE and the Beijing Institute for Nuclear Engineering set to work designing the China Experimental Fast Reactor (CEFR). By 1997, assisted by a bilateral cooperation on fast reactors with Russia, the initial design of the CEFR was complete.

The CEFR was the centerpiece of the fast breeder reactor program, designed for an electric power rating of 20 megawatts (MWe). As in the case of the pilot reprocessing plant, China's pilot fast reactor cooperation with Russia proved challenging and the project experienced severe delays. After twenty years of construction, parallel detailed design engineering work, and equipment procurement, the CEFR finally went critical in July 2010 and was connected to the power grid in July 2011. CIAE announced at the time that the CEFR would make it possible to increase the utilization of uranium fuel by 60 percent compared to current LWRs.⁶¹

Like the pilot reprocessing plant, the CEFR project was carried out to master technology intended for later deployment at an industrial scale. The CEFR was meant to provide China with experience and operations data concerning fuel and material irradiation, safety, and reliability; design feedback; data and experience for equipment development; and experience conducting lab-scale trials of process steps needed for China's future closed fuel cycle.⁶² Like the reprocessing plant, the CEFR has not routinely operated since it was commissioned, including for reasons related to technical impediments such as clogging in plant circuits.

STRATEGIC TAKEAWAYS

When the Cultural Revolution ended, China's new leaders pursued nuclear power as one of many vehicles to achieve modernization and economic development in their bid to catch up with Western nations. The focus was on nuclear power's near-term benefits—reliable electricity supply and cleaner air. Officials in China's nuclear defense program approved Beijing's plans to reward them with lucrative business opportunities in exchange for downsizing China's nuclear military-industrial complex, enhancing the concentration on peaceful uses of nuclear power.

Beginning in the 1980s, the prospect of building many more nuclear power plants prompted China's leadership to consider more strategic and national security aspects in their decision-making. Nuclear technologies for power generation and reprocessing were branded as strategic. China's nuclear R&D sector supported this by arguing that plutonium produced for weapons could provide an infinite supply of electricity, allowing China to match the prowess of advanced technology countries, especially the Soviet Union and the United States.

China's nuclear military-industrial complex was bundled together by the end of the 1980s. But as economic reforms progressed, the interests of SOEs, central government departments, and provincial governments came to the fore. Beijing viewed the SOEs' cooperation with foreign firms suspiciously until the end of the 1990s, when it resolved center-periphery conflicts with fast-developing coastal regions in its favor.

Since the 1980s, strategic thinking has predominated in program planning for the development of nuclear fuel cycle know-how and infrastructure in China. For three decades, China

focused on pilot projects for fast reactors and reprocessing intended to create a cadre of experts that could match the achievements of foreign advanced nuclear programs. Although this took longer than anticipated, China's investment in these strategic technologies during this period represented just a small fraction of its massive commitment to conventional power reactor technology.

A THREE-STEP STRATEGY: TECHNOLOGY OPTIONS AND CHALLENGES

In 2005, Chinese nuclear R&D planning officials envisioned a so-called three-step scenario for the development of China's nuclear energy program. This has served as an official point of reference throughout the 2010s including in most recent years in the Standing Committee of the State Council of Ministers.⁶³ The strategy was first openly brought forth in the Medium- and Long-Term Program for Science and Technology Development Plan for 2006 to 2020, which called for China to concentrate on using PWRs through 2020, inaugurate a transition from PWRs to fast breeder reactors from 2020 through 2050, and, beginning about mid-century, add nuclear fusion reactors to its mix of thermal and fast reactors.⁶⁴

China also prepared a Medium- and Long-Term Plan for Development of Nuclear Energy in 2005. Informed by the strategic considerations discussed above, it reflected both the three-step strategy and then premier Wen's 2005 decision to speed up nuclear power plant construction. Accordingly, this nuclear energy plan concluded that for China to reduce pollution and generate enough power, it must steamroll production of nuclear fission energy through 2050.

Specifically, by 2020, China should have an installed nuclear power generating capacity of 40 GWe (subsequently raised to 70 GWe and then lowered to 58 GWe), representing 4 percent of China's total installed power generating capacity. The document spells out that most of the added reactors would be PWRs, and that operation of these units would result in a large inventory of spent fuel and contribute to the long-term depletion of uranium

resources. Anticipating uranium becoming scarce and expensive, China would commission the CEFR and set up bigger fast reactors, including a 1,000–1,500 MWe unit by 2025. By 2050, China's nuclear capacity, based on PWRs and fast reactors, would be between 120 GWe (a low estimate where nuclear power would account for 10 percent of China's projected power generating capacity) and 360 GWe (a high estimate with a 30 percent nuclear capacity share). During the 2020s, China would construct a test fusion reactor, followed in 2040–2050 by an initial fusion power reactor, before transitioning to the third stage, when fusion reactors would complement fast reactors in the second half of the twenty-first century.⁶⁵

FUTURE REPROCESSING PLANTS AND FAST REACTORS

When R&D scientists in the 1980s urged the government to include reprocessing and the fast reactor in its 863 Program, they also proposed industrial-scale follow-on projects, supported by strategic narratives. China has erected a pilot breeder and a pilot reprocessing plant, and during 2016 and 2017 made further decisions in favor of construction during the 2020s and 2030s of industrial-scale reprocessing plants and power-generating fast reactors.

FAST BREEDER REACTOR

Upon completion of the CEFR, debate began over the size of a second breeder reactor. The choice was between a 600-MWe reactor and a bigger unit rated at 1,000 MWe or higher. Factors in the decision included China's relative lack of experience with fast reactors and the future of China's cooperation with Russia, which had greatly contributed to the CEFR project.

Since the early 2000s, China and Russia had discussed possible construction of one or two Russian BN-800 fast breeder reactors at a site in Fujian Province on China's east coast. In October 2009, an agreement was signed between CIAE, CNNC, and Russian vendor Atomstroyexport.⁶⁶ The project was shelved for undisclosed reasons. According to Chinese sources, the 800-MWe Russian reactor could not be easily accommodated by a Chinese nuclear industry that had been set up to produce equipment for generating units rated at 600 MWe.⁶⁷

Accordingly, during 2017, China prepared to break ground on a 600-MWe fast reactor construction project at the Xiapu site in Fujian Province by 2018, with the aim of completing the work by 2023. This was, to say the least, an ambitious schedule for a first-of-its-kind advanced power reactor design built in China. In mid-2017, the site was populated by personnel preparing for construction to get underway.⁶⁸ In December 2017, China officially announced that construction had begun.⁶⁹

Absent authoritative public information about this project during recent years, some speculative media reports claimed that CNNC, working with CIAE and the U.S. firm TerraPower, would begin constructing a 600-MWe fast reactor in Fujian using a TerraPower design.⁷⁰

The TerraPower concept, developed in part following past decades of fast reactor R&D at the Argonne National Laboratory in the United States, requires metallic reactor fuel; in its cooperation with Russia in the CEFBR, CIAE had focused instead on future use of oxide fuel. However, some of the media reports claimed that CIAE would nonetheless be in charge of fuel development for the TerraPower unit.

CIAE and CNNC instead prioritized an oxide-fueled 600-MWe breeder in Fujian, called the China Demonstration Fast Reactor (CDFR) or CFR-600. They promoted this project to the government to demonstrate equipment design and manufacture, power generation, system reliability, economic performance, and the development of technical standards and codes.⁷¹ The CFR-600 concept design was completed in 2014, but the detailed design was not settled until 2017.⁷² The project is described by some open sources as majority-controlled by CNNC, with other shares held by the China Yangtze Power Company, the Huaneng Nuclear Power Development Corp, and the Xiapu State-Owned Assets Group, an investment company.⁷³

In recent years, CIAE proposed following up the 600-MWe reactor in about 2030 with the first of a series of commercial breeders called CCFR-B, or an alternative version called CCFR-T meant to demonstrate transmutation. In either case, this scheme calls for the construction of many “high-breeding” fast reactors through 2050, which would “replace fossil fuels” between 2050 and 2100.⁷⁴ The December 2017 announcement of construction starting on the 600-MWe fast reactor at Xiapu included information that a bigger reactor, rated between 1,000 MWe and 1,200 MWe, may be approved by the central government in 2020. This implies that construction of this unit might begin in 2028, with the reactor ready to operate in 2034.⁷⁵ Some speculative media sources claim that instead a 600-MWe TerraPower unit may be built after the CFR-600.

During the last decade, CIAE projected that, based on expected growth in electricity demand and the need for non-carbon-emitting power sources, China might in the long term construct fast neutron reactors with an electricity generating capacity between 70 GWe and 200 GWe, compared to a forecast total nuclear capacity in China by 2050 of 400 GWe.⁷⁶ Some of CIAE’s shorter-term projections for fast reactor construction have been just as stunningly optimistic, calling for a 20-percent fast reactor share of a projected 250-GWe total nuclear capacity in China by 2050.⁷⁷ CIAE’s breeder reactor vision foresees China building fast reactors at such a rate by the end of the twenty-first century that, by the second half of the twenty-second century, over 100 units would be operating in the country, permitting “nuclear power to replace fossil fuel.” The Chinese government has not endorsed any of these plans.

When China began prioritizing the breeder in the mid-1980s, a number of countries—France, Germany, Japan, the Soviet Union, the UK, and the United States—had already launched fast breeder programs two or three decades before and operated experimental or pilot fast reactors for a decade or more. By the 1980s, these countries were preparing to set up industrial-scale

units rated between 300 MWe and 1,200 MWe, to demonstrate that the technology could be used to generate electricity reliably and economically.

China's project was intended to tap the Soviet Union's experience in the design and operation of four fast reactors—BR-5, BOR-60, BN-350, and BN-600. China's risk in doing this was modest and the potential benefits considerable, since China's initial goal was limited to gaining enough knowledge to successfully implement a project for a small experimental reactor rated at 20-MWe. This project would replicate others' previous efforts, incorporate their lessons learned, and, most importantly, include China in the field of advanced nuclear power countries having technology that offered the possibility of virtually unlimited future nuclear fuel supply.

The decisionmaking environment for the fast reactor is quite different today than three decades ago. During the intervening years, none of the above countries succeeded in building and then operating an industrial-scale demonstration fast reactor to produce electricity using plutonium fuel at a self-sustaining cost, and all encountered technical challenges, which translated in some cases into an erosion of political support. The most important issues were sodium fires, equipment and engineering problems, and severe accident concerns. The cumulative impact of these contributed to decisions by governments in France, Germany, Japan, the UK, and the United States not to license planned fast reactor construction projects and/or to prematurely close reactors that were licensed for operation. The record of technical issues that have daunted fast reactor programs since the mid-twentieth century includes the following:

- **Steam generator integrity:** Sodium reacts violently with air and even more so with water, and fast reactors have experienced very damaging sodium fires on occasions when liquid sodium leaked.⁷⁸ A number of leaks and fires occurred in early-design steam generators in France, the UK, and Russia. Leaks were caused by steam generator manufacturing defects or by cracks in equipment caused by material fatigue and corrosion.
- **Other sodium leaks and fires:** Many of these leaks were small and were detected by periodic inspections, but larger ones include four leaks at BN-600 involving between 300 kilograms (kg) and 1,000 kg of sodium. A leak of 640 kg of sodium at Japan's Monju unit resulted in a serious fire, which spread by dispersed sodium aerosols because sodium circuits were not emptied—the sodium containment was not fully inerted and ventilation systems failed to operate.⁷⁹ Leaks were caused by faulty equipment design and by fabrication, materials-related issues, corrosion, and operator error.⁸⁰
- **Equipment, materials, and engineering issues:** Defective design, inadequate materials, and faulty operating procedures have led to myriad problems in several reactors. Design flaws in some cases caused heat exchangers and pumps to fail. French regulators raised issues concerning the integrity of core support structures. Equipment immersed

in sodium proved in some cases inaccessible to inspection, leading to maintenance problems and long outages. Material weakness led some equipment to crack when exposed to sodium for long periods. Control rods failed in reactors in Germany, France, and the UK due to deposits of oxidized sodium aerosols. Some critical equipment in several reactors was initially made with steels that proved vulnerable to cracking in welded hot areas and caused long repair outages. These materials were later replaced by others that are stronger and corrosion-resistant.⁸¹ Similar problems also challenged LWR development. For LWRs these were overcome only after improvements, backed by decades of operation at several hundred reactors, were made. It is possible that over time many or most of these issues faced by fast reactors might be solved, provided however that reactors accumulate sufficient operating experience.

- **Incursions of air and impurities:** Incursion leads to the formation of solid particulates and other compounds that cause harm by provoking secondary reactions and buildup of deposits. These can cause component damage, so limiting them is essential to assuring long component and system lifetimes and reliability. Fast reactors—SPX in France, PFR in the UK, and BN-600 in Russia—suffered incursion events between 1987 and 1991 that led to long outages. Today, sodium purification equipment is well developed and the risk of incursion might be less.
- **Fuel integrity issues:** A number of reactors in France, Germany, Russia, and the UK suffered cladding ruptures, especially during initial operation. In some cases, problems were caused by inappropriate austenitic steel used as cladding; in some other cases, they were caused by issues related to the geometry of fuel design. Integrity issues inhibited irradiation to high burnup levels desired for fast reactors. The most serious problems occurred during early years of fast reactor programs. These events have been reduced over time by better fuel design and the use of stronger materials. The basic problem is that burnup levels for sodium fast reactors are three or more times greater than for LWRs, and the fuel must withstand higher temperatures.⁸²

Governments and industries have prioritized addressing the above issues to improve the safety, reliability, and performance of future fast reactors. In some cases, remedial actions were taken at operating reactors. A key area of development is fast reactor steam generator systems: in future reactors, these must be equipped for rapid hydrogen detection and, in that case, they must respond by promptly shutting down and depressurizing affected steam circuits. Future steam generators may also be outfitted with protective casings resistant to extreme sodium-water reactions; safety membranes may limit pressure increases in the case of a sodium-water event. In modern reactors, sodium leaks might be limited by the use of improved materials and by better welding of sodium-boundary equipment.

Beginning in the 1990s, implementation of some of these measures led to a significant reduction in sodium-water interactions at French and Russian reactors.⁸³ But challenges remain: Some equipment and systems in future reactors may be designed to have double walls, but this could cause welding problems in critical components such as steam generators. Other proposed approaches to improve system integrity and safety, such as adding a reactor loop (for example, using molten salt), will likely prove too expensive.

Leaks and fires have prompted improvements in equipment design; operations procedures for sodium circuits; use of redundant leak detection systems; fire protection including emergency emptying of sodium circuits; compartmentalization of sodium areas to inert or cut off ambient air supply in the case of fire; and use of fire-resistant surface materials.

In light of experience, future reactors must be designed with new features: diversified safety systems to mitigate the risk of common-mode failures; improved cores that exclude or limit probability of core collapse leading to a serious accident;⁸⁴ primary circuits limiting buildup of gas; and improved maintenance technology for equipment immersed in sodium, including ultrasonic instrumentation to facilitate inspection. To handle some accident scenarios, it will be necessary to be able to completely remove the reactor fuel load. Other safety challenges include seismic resistance, anti-flood measures, severe accident management, geometric stability of the core, and reliability of control rods.⁸⁵

On balance, technical reliability is a major challenge standing in the way of a commercial future for this technology, including in China. In a few cases, and for limited periods, fast reactors have demonstrated a capacity factor (the ratio of actual electric power output over a period of time, compared to the output that would be achieved if the plant operated at full power rating without interruption) between 50 percent and 75 percent—but to compete with LWRs under market forces, a capacity factor of 90 percent may be necessary. Improving fuel, in-service maintenance, component reliability, and the reduction of sodium-related events will be paramount to achieve this. Most sodium leaks and fires have not strictly speaking been nuclear safety-significant events, but they have greatly contributed to low capacity factors during fast reactor operation.⁸⁶ Experience with the Russian BN-600 suggests that greater reliability in future reactors may be possible: after thirty-five years of operation, the BN-600 has produced two-thirds of the electricity generated by all of the world's nineteen fast reactors. It has performed at a capacity factor of 77 percent during the last two decades and its licensed lifetime may be extended to sixty years.⁸⁷ The improvements in BN-600 operation are well-known to China's breeder program through CIAE's collaboration with Russian R&D institutions.

INDUSTRIAL REACTOR-BUILDING CAPACITY

Should China go forward with plans to set up advanced nuclear power installations including industrial-scale fast reactors, these projects would be implemented by a nuclear industry that,

without interruption since the early 1980s, has been aggressively developed and indigenized with Chinese government assistance and foreign technology inputs. Before 2030, China will likely have set up 100 nuclear power plants on its territory. Especially given China's relatively low level of economic development until the 1980s, this feat is considerable. But it is not unprecedented. The United States built over 100 nuclear power reactors in about the same amount of time; France built almost sixty units, and Japan nearly that many, over the span of half a century.

Since the 1980s, China has organized its nuclear power industry around a small number of very big SOEs, chief of which are CNNC and China General Nuclear Power Group (CGN, formerly CGNPC). Each of these firms, particularly CNNC, has numerous subsidiaries and owns shares in still more companies, giving them great influence or, in some cases, direct control over most nuclear power investment and construction activity in China. Both CNNC and CGN are vertically integrated companies that invest in, build, and operate nuclear power plants. A third such company was established in 2015, when the State Nuclear Power Technology Corporation merged with China Power Investment Corporation, a leading Chinese utility company, to form the State Power Investment Corporation (SPIC). Until now, these firms have spearheaded all of China's nuclear power plant construction. Nearly all the nuclear power plants they have built or are constructing are PWRs. Over time, China has succeeded in claiming control over intellectual property rights to this technology. After building nuclear power plants based on foreign technology its owners agreed to share, Chinese firms modified the technology and branded the results as Chinese intellectual property.

In step with the central government's decisions in the late 1970s to invest in nuclear power and in the mid-2000s to accelerate nuclear power plant construction, China's heavy industry has built up the capacity to make equipment needed for serial realization of multi-reactor nuclear power plant projects. Investment began during the 1980s to support construction of a line of PWRs that CNNC had pioneered with assistance from a number of foreign industry partners. When China began scaling up this infrastructure to meet the technical demands of bigger units, it encountered difficulties and had to invest more in forging, component manufacture, and quality control. In tandem with the 2005 decision to accelerate the pace of China's nuclear power construction, five select state-owned power-engineering and heavy equipment-making companies spent \$4.5 billion to build up their capacities.⁸⁸ Today, these firms are equipped to annually produce the critical nuclear equipment (sufficient reactor pressure vessels, core internals, and control rod drive mechanisms)—and up to twenty-seven steam generators, thirty primary pumps, and fifteen turbine generators—to equip between eight and ten new nuclear power plants per year.⁸⁹

Should it indefinitely sustain this industrial capacity, China would meet the requirements for a continued expansion of its installed nuclear capacity at all but the highest current

projections through mid-century. Estimates from Chinese sources and organizations have varied widely about how much nuclear power capacity should be added during the next three to four decades. Attaining an installed nuclear capacity of 300 GWe by 2050—a baseline reference found in some Chinese studies—would mean adding about eight reactors per year until 2050.⁹⁰ Considered solely on the basis of equipment-making firms' current capacity, this might be feasible. Compared to the United States, where thirty utility companies and seven vendor firms built a variety of plant designs at a rate of five units per year, China would benefit from ongoing industry standardization and consolidation.

China has also invested in transitioning from PWRs to fast reactors by 2050. Since the late 1960s, CIAE, in cooperation with Russian industry, has been working on fast reactor neutron behavior and thermohydraulics, development of sodium-handling equipment, reactor materials, and fuel. China also set up three dozen experimental facilities and testing circuits for fast reactor R&D, many concerned with the critical field of sodium management. All told, over 100 Chinese institutions are now involved in efforts to set up an industrial-scale fast reactor. Since 2011, this work has accelerated to demonstrate the manufacture of components needed for the 600-MWe-and-larger units and design of critical and specialized equipment for reactor vessel support, seismic isolation, neutron detection, passive reactor shutdown, and remote inspection of equipment under sodium.⁹¹

Because China came relatively late to the fast reactor—and was also behind the curve for designing, constructing, and operating an industrial-scale unit—it can take advantage of lessons learned from earlier foreign projects. The design of the CEFR incorporated operational experience from previous projects on sodium fire mitigation, and the CEFR has better detection and alarm systems, a modern emergency ventilation system, sodium fire suppression equipment, graphite-based fire extinguishers, and steel covers and insulated concrete surface covers.⁹²

China joined multilateral expert groups—the Generation IV International Forum (GIF), the IAEA's International Project on Innovative Reactors and Fuel Cycle (INPRO), and the IAEA Technical Working Group on liquid metal fast reactors—to benefit from more experienced states' advanced reactor development programs. GIF was established to support international cooperation on six reactor designs, including sodium fast reactors, and INPRO was established to encourage generic cooperation on reactor and fuel cycle innovations, including fast reactors. They were not, however, intended to develop or share confidential intellectual property, and individual members continue to focus on their own unique, proprietary, and, in some cases, divergent country-specific engineering solutions.

In December 2017, China inaugurated construction of a 600-MWe fast reactor that is scheduled to be finished in 2023. Some experienced fast reactor engineers outside of China suggested that the proposed five-year construction schedule is not realistic because China does not

have enough fast reactor design, commissioning experience, and other resources to quickly build an industrial-scale reactor so soon after completing the CEFR. Other sources in China said that the 2023 deadline is considered by the government to be “flexible” due to the pioneering status of the project.⁹³ CIAE itself is aware that the ambitious schedule—and perhaps even its value as a showcase for advanced technology—will be challenging, as Chinese firms are forced to manufacture critical equipment for the reactor before GIF can address related technical issues for the design of more advanced equipment.⁹⁴ Chinese project engineers have likewise warned that the CEFR went over budget twice during implementation because critical components had to be procured from abroad, because China lacked fast reactor project management experience, and because Chinese engineers had few references for the integrated pool-type reactor design that had been chosen.⁹⁵ Some experts interviewed for this report cautioned that the sooner China aims to break ground on the 600-MWe fast breeder demonstration reactor, the less confidence they would have that the project will be completed on schedule. Should China, in light of its limited experience with fast reactor engineering, form foreign partnerships to realize this project, the administration, oversight, and requirements of collaborative decisionmaking would inevitably cause delays.

When the State Council ordered a penetrating nuclear power safety review after the Fukushima disaster, experts identified safety design weaknesses in the just-commissioned CEFR. These included containment issues; inadequate decay heat removal from spent fuel in the case of a long-term loss of power; and loss of heat sink for design basis accidents. Separately, experts found weaknesses in defense against certain severe accident scenarios.⁹⁶

Russian industry—which supplied a considerable share of the technology basis and key equipment for the CEFR—continues to contribute to China’s fast reactor program. The 2009 agreement to build the BN-800 in China is in abeyance,⁹⁷ but China and Russia signed a nuclear cooperation agreement in November 2016 that included future fast reactor development collaboration.⁹⁸

China has also cooperated with the United States on the development of closed fuel cycle technology related to the fast reactor. In 2006, the United States launched the Global Nuclear Energy Partnership (GNEP), a multilateral forum to cooperate on advanced nuclear power-related technologies. China joined GNEP the same year and, in 2007, the United States and China concluded a Bilateral Civilian Nuclear Energy Cooperative Action Plan meant to “collaborate on research to further develop advanced nuclear fuel cycles with the objective of nuclear safety and non-proliferation.”⁹⁹ One working group concerned fast reactor collaboration, and it continued to convene during the 2010s. As part of this, China has enlisted the cooperation of U.S. national laboratories in areas including reactor core physics, modeling of fuel cycles, and development of fast reactor metallic fuel.

As previously discussed, the U.S. firm TerraPower agreed on the outlines of collaboration with CNNC and CIAE on the joint development of a fast reactor, the conceptual design for which relies on previous U.S. experience, principally at Argonne National Laboratory. The extent of U.S. cooperation with China in this field is subject to U.S. export control restrictions.¹⁰⁰ Unofficial media have reported that U.S. export controls on sensitive technology were adjusted by the U.S. Department of Energy to permit sensitive but unclassified technology transfer from the United States to China for the TerraPower project.¹⁰¹ However, according to U.S. officials, security and nonproliferation concerns have prompted political directors in the U.S. government to occasionally discourage U.S. industry and government entities from contributing to some aspects of China's fast reactor program.

REPROCESSING

China's assertion that it aimed to close the nuclear fuel cycle at the industrial scale meant that, at some point, it would construct facilities to reprocess its spent fuel, make new fuel using the recovered fuel materials—uranium and plutonium—and dispose of the residual wastes generated from reprocessing and fuel fabrication. In 2014, the Chinese government described the government's policy on management of spent nuclear fuel:

China's spent fuel management policy is to implement the reprocessing of spent fuel and to extract and recover uranium and plutonium materials, so as to achieve maximum use of resources, reduce the generation of high level radioactive wastes (HLW) and to ensure the safety of spent fuel management and the public safety, and to lower the risks to the future generations.¹⁰²

When China chose Westinghouse over French firm Areva to provide the blueprints for future PWRs in 2006, it also took a step toward the realization of an industrial-scale reprocessing plant to follow the pilot plant then under construction at Jiuquan. Areva and CNNC concluded a memorandum to build a Chinese reprocessing plant based on Areva technology used in installations with a capacity of 800 MTHM per year (MTHM/y) in France and Japan.

Beginning in 2006, the two sides failed for a decade to agree on terms for this project, leading some Chinese experts to favor construction of a smaller plant using indigenous know-how. France and China differed over the price and French officials raised concerns about national security.¹⁰³ U.S. government officials openly objected to China's designs to establish a commercial-scale reprocessing industry, and discreetly urged France not to go forward with a bilateral reprocessing agreement that might involve the sale of Areva shares to CNNC.¹⁰⁴

According to a Chinese executive, the Communist Party's leadership formally approved CNNC's industrial-scale reprocessing plans sometime in late 2014.¹⁰⁵ Since then, technical discussions between French and Chinese government agencies and firms concerning

details of the bilateral reprocessing project were conducted on the understanding that an 800-MTHM/y reprocessing plant using Areva technology would be erected by 2032 at one of a number of proposed Chinese locations, and that full-scale operation of the plant would commence by 2035.¹⁰⁶

Senior executives from Chinese reactor-owning organizations said in November 2017 that China intends to carry out both the 800-MTHM/y reprocessing plant project based on foreign assistance and a 200-MTHM/y “indigenous and intermediate-sized” reprocessing plant. Both projects, they said, are called for under official central planning decisions covering the period 2011 to 2020, including the Thirteenth Five-Year Plan, and implementation is subject to ongoing deliberations of the Standing Committee of the State Council of Ministers. According to these officials, the State Council formally decided in December 2016 to make the necessary investments for both industrial-scale reprocessing plants.

Pre-construction site preparation activities began in 2015 on the intermediate-sized reprocessing plant in the Jinta district in Gansu Province, north of Jiuquan. Officials in 2016 described the intermediate-sized plant as having a design throughput of 200 MTHM/y and a completion date of 2025, five years later than originally foreseen.¹⁰⁷

SPENT FUEL

So far, virtually none of China’s power reactor spent fuel has been reprocessed, reflecting Beijing’s overwhelming focus on nuclear power plant construction and operation. Instead, China has taken action to store its spent fuel for at least two decades, primarily at the reactor sites. This is consistent with the management of spent fuel in many other nuclear power programs, and China is using technologies for spent fuel storage that are conventionally deployed worldwide.

By 2005, China had accumulated a total of 1,100 metric tons (MT) of spent fuel. By 2020, reflecting the dramatic increase in China’s reactor population, this stockpile should increase sevenfold.¹⁰⁸ Nearly all of China’s power reactor spent fuel is being stored at the power plant sites.

Currently, over half of China’s installed nuclear capacity is based on a standard French PWR model. Spent fuel from these reactors is stored in water-filled pools designed to hold approximately ten years’ worth of spent fuel from normal operation. China is also building PWRs based on the U.S. AP1000 design. Spent AP1000 fuel will be stored in a water-filled pool with the same capacity of ten years of normal plant operation.¹⁰⁹ Since 1992, China has operated a twin-unit Russian-design VVER PWR at Tianwan, which is also equipped with spent fuel pools. In 2016, these pools were reportedly nearly full and Russian industry was tasked with adding more storage capacity during ongoing construction of additional VVERs at the

site.¹¹⁰ China's first uniquely designed power reactor, Qinshan-1, has sufficient capacity at the site to store all spent fuel through 2025; two follow-on units, Qinshan Phase II, have sufficient capacity through 2022.¹¹¹ Storage capacity at existing reactors has been expanded, and new PWRs are equipped with twenty years' on-site spent fuel storage capacity.¹¹²

In addition to its growing number of PWRs, China is also operating a nuclear power plant called Qinshan Phase III, which is equipped with two CANDU 6 (Canadian Deuterium Uranium) pressurized heavy water reactors fueled with natural uranium. The two reactors discharge about 5,000 small bundles of spent fuel per year. These are stored initially in a water-filled pool with a capacity of just under 38,000 bundles, which is the amount of spent fuel discharged after about seven years of normal operation. Since 2008, China has been constructing a series of modular dry storage facilities at the site for the longer-term storage of this spent fuel. Each module has the capacity for 24,000 spent fuel bundles. China plans to construct a total of eighteen modules, assuring sufficient capacity to store spent CANDU fuel until at least 2042.¹¹³

China has also taken steps to store spent fuel away from the reactors. Both the pilot reprocessing plant at Jiuquan and the intermediate-scale reprocessing plant at Jinta are designed with head-end facilities to receive and store spent fuel prior to reprocessing. The head-end facilities at Jinta and/or Jiuquan may, in the future, be large enough to store several thousand metric tons of spent fuel and could, in principle, be continually expanded should China decide to move larger amounts of spent fuel away from reactor sites that are filling up.¹¹⁴

That option may be under consideration in light of recent political challenges China has experienced. In part related to political and regulatory developments after the Fukushima accident, Beijing has had difficulty securing approval from local and provincial authorities in eastern China to site future centralized spent fuel storage locations on their territories. During the 2000s, the spent fuel wet-storage capacity at Jiuquan was expanded from 500 MTHM to 760 MTHM, but its use was delayed by regulators, which threatened to suspend operations at the Daya Bay nuclear power plant for lack of spent fuel storage capacity. The emergency was alleviated by shunting spent fuel from Daya Bay to the nearby Ling Ao nuclear power plant.¹¹⁵ Before 2030, China will likely need additional storage space to accommodate spent fuel discharged from currently operating nuclear power plants.¹¹⁶

China's future rate of spent fuel accumulation will depend on how long its existing nuclear power plants are operated, and on how many more nuclear power plants it builds. China expects to continue to add to its nuclear electricity generating capacity in coming years, but the government has not established firm planning targets for installed capacity beyond the end of the Thirteenth Five-Year Plan in 2020. Were China to expand capacity to 150 GWe by 2035, it might accumulate about 21,400 MT of spent fuel by then. If, instead, China expands

capacity to 450 GWe, its accumulation would be perhaps about 29,400 MT by 2035.¹¹⁷ By comparison, the United States operated as many as 100 power reactors for over sixty years and its cumulative spent fuel inventory has reached about 70,000 MT.¹¹⁸ The total amount of power reactor spent fuel in the world is currently about 300,000 MT.¹¹⁹

The averted shutdown at Daya Bay over lack of spent fuel storage capacity has led reactor owners to consider the possible consequences of any future short-term bottlenecks and the need for China's reprocessing plans to be realistic. It is obvious to Chinese planners that an aggressive reprocessing schedule would in theory take pressure off reactor owners and politicians to provide for additional interim spent fuel storage capacity.¹²⁰ Independent of plans to provide for sufficient storage capacity, some reactor owners may experience logistic and regulatory complications arising from changes in in-core fuel management—implying that fuel will remain in the core for longer periods, which increases its heat load and alters its radioactive contents. Chinese executives privately express concerns that, while it proved relatively simple to move spent fuel from Daya Bay to an alternative location, a Chinese reactor owner might be hostage to commercial pressure from competitors, especially CNNC, in a different situation.¹²¹

Unlike Japan, South Korea, or Taiwan—where policymakers are under greater near-term pressure to secure adequate storage for power reactor spent fuel—China is a very big territory with many remote areas. For at least most of this century, China could technically manage all of its power reactor spent fuel by storing it at reactor sites and off-site locations, using water-filled pools followed by dry storage. On the basis of experience and licensing in other nuclear power programs, China could safely and reliably store its spent fuel without alteration through mid-century and for at least several decades beyond. At some future time, however, China will need to make policy and engineering decisions about disposing of its spent fuel in the long term.¹²²

According to China's nuclear technology development plan, "spent fuel reprocessing is the vital link in the closed fuel cycle, especially for the transition from an advanced thermal reactor to a fast reactor-based fuel cycle."¹²³ Should China set up a network of industrial-scale fast reactors, each might require an initial inventory of several tons of plutonium, most of which would be loaded into the core. Once the fast reactors begin operating, plutonium will be supplied to the system in two ways: by the reactors converting uranium-238 in driver and blanket assemblies in the reactor cores to plutonium-239 through neutron capture, and by the reprocessing of spent fuel from thermal reactors that continue to operate. Each fast reactor would provide more plutonium than it needs to operate; eventually, each will generate enough plutonium for the initial core of a new fast reactor. The rate of production of excess fissile material in the fast reactor system is called doubling time.¹²⁴ This depends on variables including the total fissile material mass, reactors' breeding ratio (the rate of plutonium

production from fertile isotopes divided by the plutonium consumption),¹²⁵ and the amount of plutonium losses during fuel fabrication and reprocessing. Doubling times might be as short as five years for some aggressive breeder reactor deployment scenarios or as long as twenty years in scenarios where the rate is comparatively relaxed. Some scenarios envisage fast reactors reducing existing plutonium inventories by “burning” more plutonium than they generate; very ambitious breeder reactor deployment scenarios call for deploying many reprocessing plants to accommodate projected plutonium demand. Chinese experts have derived numerous theoretical scenarios and calculations for both burning and breeding plutonium.¹²⁶

In some scenarios, theorists postulate that a country like China might transition from a nuclear power system mostly based on PWRs to a system relying on fast reactors over a period of several or many decades. How quickly a country could effect that transition would depend on its technology resource base (in particular, its capacity to provide fuel cycle infrastructure including reprocessing and fuel fabrication plants), the rate of growth of its electricity demand, and other factors. Theoretically, if a number of nuclear power-producing states attempted to organize a coordinated global transition from LWRs to fast reactors, a sevenfold increase in reprocessing capacity might be required over half a century.¹²⁷

In reality, no country’s nuclear energy program has so far deployed more than one large industrial demonstration fast reactor fueled with plutonium at any time, and a coordinated multinational deployment of fast reactors has never been attempted. Europe and Japan set up reprocessing plants in tandem with successive deployment of pilot and demonstration fast reactors, but the fast reactors were prematurely shut down or not built and the reprocessing plants were used instead to supply plutonium for MOX fuel for existing thermal reactors. Considering this experience, China would need to carefully match the supply of its future plutonium with its real plutonium demand.

Should China go forward with its plan to reprocess its spent fuel, it would follow in the footsteps of a number of other countries, including the United States, France, Germany, Italy, Sweden, Switzerland, Belgium, Netherlands, Russia, and Japan. Most of the world’s reprocessed power reactor spent fuel was handled at reprocessing installations in France. In the 1970s, French government-owned Areva established spent fuel reprocessing and MOX fuel fabrication as a commercial business activity in tandem with France’s decision to accelerate its construction of nuclear power plants. Beginning in the 1980s, Areva built a reprocessing plant complex at La Hague that currently has the capacity to reprocess 1,700 MT of spent fuel per year. As of 2005, about 90,000 MT of the 276,000 MT of spent fuel from civilian nuclear power generation had been reprocessed worldwide. Today, perhaps 120,000 MT in power reactor spent fuel has been reprocessed.¹²⁸

All of the world’s industrial spent fuel reprocessing plants were designed for a technology called the Plutonium Uranium Redox Extraction Process (PUREX), which uses nitric acid

to dissolve spent uranium oxide fuel and relies on organic chemicals to extract pure uranium and pure plutonium from the solution. This process was developed after World War II and adopted, beginning in the mid-1950s, over two decades by France, Germany, Japan, the UK, the United States, and the Soviet Union. PUREX succeeded in large part for three reasons: it demonstrated a high recovery rate for plutonium, thanks to the use of the low-cost organic reagent tri-*n*-butyl phosphate; it supported recycling of recovered uranium; and it solved certain waste management issues more effectively than other alternative processes.¹²⁹

In the 1980s, when Beijing announced it would establish reprocessing infrastructure for its future power reactor spent fuel, China likewise intended to use PUREX technology and designed the pilot plant for PUREX. According to Chinese scientists, PUREX is preferred because it is well understood and is the global industry standard. For the same reasons, scientists say that China has also chosen PUREX as the technology basis for the 200–MT per year (MT/y) reprocessing plant now under construction.¹³⁰

Should spent fuel reprocessing continue as an industrial activity throughout this century, however, PUREX may be replaced before or by 2050 by more advanced technologies for reasons of nonproliferation, economics, waste management, and environmental impact.

On security and nonproliferation grounds, a disadvantage of PUREX is that it generates pure separated plutonium from spent fuel. To address this concern, French scientists developed a process for the co-extraction of actinides (COEX) to retain a uranium/plutonium mixture through the end of the process, in some variations creating a uranium/plutonium blend feedstock for MOX fuel fabrication.¹³¹ This or similar process technology may be designed into new reprocessing plants—including a plant that Areva may build in China—though the COEX process is not without technical challenges.¹³²

Current R&D efforts to go beyond PUREX in China are driven by ongoing improvements and technological developments in reactor technology and power reactor fuel. PUREX was not designed to treat more challenging spent fuel types, such as fuels with high plutonium content, non-oxide matrices, and high discharge burnup (the amount of energy generated in a reactor per initial mass of fuel). The global nuclear industry has over several decades—especially since market forces began encouraging industry to use resources more cost-effectively—increased the burnup levels of power reactor fuel. For mainly economic rationales—reducing the amount of downtime for refueling, reducing the amount of fresh fuel that must be loaded into reactors, and reducing the amount of spent fuel that must be discharged to generate a given amount of energy¹³³—burnup has risen from mid-30 GW days per MT of fuel (GWd/MT) to nearly 50 GWd/MT today.¹³⁴ In the future, the burnup level for some LWR fuels may approach 90 GWd/MT, implying that, by mass, the fuel would be producing three times the amount of energy than during the early years of nuclear power generation.¹³⁵

As burnup increases, spent fuel exhibits higher concentrations of a large variety of fission products, making it more difficult to reprocess. There may be buildup of particulates that resist dissolving. Reprocessing very high burnup fuel may require facilities equipped with additional neutron shielding, designed for a higher rate of solvent degradation, higher operating temperatures, and different materials and processes for high-level waste (HLW) treatment to cope with higher decay heat, higher neutron outputs, and higher inventories of heavy nuclides. China's nuclear industry and R&D sector are fully aware of these trends. Chinese reactor owners frequently cite ongoing increases in the burnup of spent fuel as a factor in urging policymakers to ensure that, in parallel with planning for reprocessing, China provides for sufficient interim spent fuel storage capacity. At the R&D level, Chinese experts are exploring complex separation scenarios related in part to anticipated future fuel strategies and technologies.¹³⁶

PARTITIONING AND TRANSMUTATION

Chinese experts frequently say that waste management, especially partitioning and transmutation (P&T), is a key rationale for both reprocessing and fast reactor deployment.

The goal of P&T is to change the long-lived actinides into fission products and long-lived fission products into significantly shorter-lived nuclides, creating nuclear waste products that decay in a few hundred years compared to untreated waste that would remain radiotoxic for over 100,000 years. If successful, P&T would also permit the reduction of HLW inventories and the heat load of geological repositories,¹³⁷ and eliminate most of posterity's burden for managing today's waste from nuclear electricity production. In the Chinese view, "For advanced reprocessing of future used fuels, the objective is not only to recover plutonium and uranium, but also to manage actinides and fission products."¹³⁸

Closed fuel cycle technologies are intended to dramatically reduce the radiotoxicity, or the hazard to human cell tissue, posed by spent fuel. Plutonium is the main contributor to long-term radiotoxicity in spent fuel and it can be efficiently removed using PUREX. Other long-lived and poisonous radionuclides that are currently disposed of as waste from PUREX reprocessing include the so-called minor actinides (MA), of which neptunium, americium, and curium are the most significant. Removing the plutonium from spent fuel can reduce the radiotoxic inventory of spent fuel by a factor of ten. If MA are separated and then burned in a fast reactor, the reduction factor might be higher than 100. Neptunium can be removed by adjusting PUREX, but not americium or curium.¹³⁹

However, the nuclear science challenges of P&T are extremely formidable. Recovery of MA is difficult because the chemical properties of these elements are highly similar under conditions that would likely be encountered in a solvent-extraction process. Selective separation of americium and curium from lanthanide fission products, and separating the americium from the

curium, are foreseen in some advanced scenarios but the similar chemical behavior of the elements involved make these challenges among the most difficult in advanced reprocessing.¹⁴⁰

A number of processes have been developed that go beyond PUREX to facilitate P&T, but these will only be relevant for nuclear power applications if they can be made to work at the industrial scale and if fast reactor technology is commercialized.¹⁴¹ Scientists hope that the world's extensive cumulative experience with PUREX will lead researchers to design separation systems likewise based on solvent extraction that will facilitate industrial-scale P&T. Research on the engineering of systems for industrial scale application is being considered.¹⁴²

Caution, however, is warranted because MA separation has been the subject of active research for half a century. Researchers need better engineering tools, including spectroscopic advances, supported by computational techniques to develop processes that are simple and economical enough to be applicable for nuclear power.¹⁴³ Two decades or more may be required before nuclear power might benefit from this P&T research.¹⁴⁴

CHINA AND ADVANCED REPROCESSING

Chinese research on P&T started during the early 1980s, and scientists more recently began R&D on an advanced PUREX process, in part to meet the challenge from spent fuel with higher burnup levels.

A key element of Chinese advanced PUREX research is the application of salt-free organic reagents to improve PUREX. One focus is on problems in PUREX related to the behavior of technetium in the dissolved spent fuel that can lead to excessive plutonium accumulation and failure of separation of plutonium and uranium.¹⁴⁵ Another area of Chinese research is to achieve efficient separation of neptunium from the plutonium product stream. Some Chinese efforts on separation chemistry have concentrated on recovery of all actinides—uranium, plutonium, neptunium, americium, and curium—as a group, leaving the shorter-lived heat-emitting elements—cesium and strontium—in the HLW. China has focused on the use of so-called trialkyl phosphine oxides (TRPO) to achieve total actinide recovery from HLW generated from PUREX reprocessing. Some experiments were carried out using this process to treat HLW generated by China's nuclear weapons program. More recently, China has also designed a process for the separation and recovery of actinides and lanthanides, including separating and recovering strontium from HLW.¹⁴⁶

China is also working on the separation of actinides from lanthanides, and has achieved lab-scale success using chosen extractant organic chemicals.¹⁴⁷ But researchers have also experienced degradation of extractant chemicals from high radiation fields, and this problem must be addressed before China can consider moving toward industrial-scale applications.¹⁴⁸ The Chinese TRPO process was tested successfully in Europe, but it was judged

to have drawbacks including extra process steps that may discourage industrial application, certain fission products interfering with the separation, and high nitric acid concentrations in the actinide/lanthanide mixture.¹⁴⁹

PYROPROCESSING

Scientists planning for a closed fuel cycle anticipate that after aqueous PUREX reprocessing is mastered, China will develop and deploy a nonaqueous technique called pyrochemical processing, or pyroprocessing, to supply recycled fuel for future fast reactors. Pyroprocessing has been in development since the 1950s, originally by the United States and the Soviet Union in tandem with their fast reactor programs, and is now also being researched and developed in South Korea, Japan, India, and Europe.

In pyroprocessing, spent fuel is chopped, heated, and turned into a powder, which is subjected to high heat that burns off volatile fission products (krypton, xenon, iodine, and cesium). The powder is transformed into a metal that is placed into a bath of molten salts, such as lithium chloride or potassium chloride. The bath with the metallic fuel material is then subjected to an electric current (so-called electrorefining process), and the metal dissolves and separates into component stages. Pure uranium collects at a steel cathode immersed in the bath, and the transuranic material (plutonium, neptunium, americium, and curium) and fission products (cerium, neodymium, and lanthanum) are removed. The uranium is brought to a casting furnace where it is used to make new fuel. The transuranic elements and fission products can be conditioned for disposal in a geological repository or also processed in a casting furnace to make fuel for a fast reactor.

Pyroprocessing chemistry is well-understood. Since metallic fuel would likely be used in future fast reactors because it is more efficient than oxide with respect to heat conductivity and breeding ratio, pyroprocessing may be appropriate since it involves handling of metals at high temperatures. In the GIF program, advocates assert that pyroprocessing has specific advantages for advanced closed fuel cycles. These include: integration of reactor operation, reprocessing, and fuel fabrication; resistance of molten salt and liquid metal solvents to radiation damage for high burnup fast reactor fuels; reduced quantities of waste; and inherent actinide partitioning. The radiation resistance of molten salt implies that fuel cooling times may be shortened. Integration of fuel cycle process steps may lead to more compact installations. Criticality dangers might be reduced because the process will generate relatively impure product fractions.¹⁵⁰

There are also potential drawbacks to pyroprocessing. These include: possible misappropriation of separation technology to produce pure plutonium; the aggressive behavior of molten salts and liquid metals; the material science and maintenance challenges concerning equipment in a commercial-scale plant that must withstand high operating temperatures between

400 and 1,000 degrees Celsius; and the daunting engineering challenges of adapting what has been, until now, a limited-batch process requiring a highly pure environment to handle industrial quantities of spent fuel.

China's recent engagement in this field has been generic compared to the experience accumulated by the United States, South Korea, and Russia. China has, so far, not processed irradiated nuclear fuel in specially designed pyrochemical research installations. Following the establishment of GNEP in 2006, China and the United States began cooperating on the development of high-burnup fast reactor metallic fuels, casting technology for uranium/plutonium fuel, and pyroprocessing flow modeling.¹⁵¹ Some Chinese experts have suggested that Beijing aims to set up a pyroprocessing facility for spent fuel by 2030 or 2035.¹⁵² To date, however, most Chinese pyroprocessing research is academic and concerns, for example, measurement of basic parameters including on uranium in molten chloride salts, simulations of fuel dissolution in molten salts, and properties of molten salts. China is currently not operating any pyroprocessing installations.¹⁵³ Because CNNC has a monopoly on China's aqueous reprocessing activities, it was rumored in 2017 that CGN might seek pyroprocessing R&D partners in South Korea; this was denied by CGN officials.¹⁵⁴

OTHER ADVANCED FUEL ISSUES

Should China build and operate fast reactors in addition to its PWRs, it will have to set up infrastructure dedicated to producing fast reactor fuel and reprocessing the spent fuel. Because of differences in radioactivity and isotopic composition, this fabrication and reprocessing activity would be in addition to and separate from China's ongoing fabrication and reprocessing of spent fuel from PWRs. If China deploys a large fast reactor in the near term, it might reprocess the spent fuel using currently available aqueous technology.

MOX Fuel Fabrication

Unlike LWRs, in which neutrons emitted by the fuel are slowed down by water to increase the probability that they will cause an exothermic fission reaction, breeder reactors rely instead on the greater amount of energy contained in fast neutrons. Sustaining a chain reaction in a fast reactor requires fuels richer in fissile material. In most fast reactors, highly enriched uranium (HEU) or plutonium is used. The fuel is normally either metal alloy or MOX. Russian fast reactors have operated mostly using metallic HEU fuel. Fast reactors in France and Japan have instead used MOX fuel.

MOX fuel currently accounts for about 5 percent of the world's LWR fuel. So far, about 2,000 MT of MOX fuel has been used in about forty of the world's 450 power reactors, mostly in Europe, consuming about 10 MT of plutonium per year. MOX use in LWRs has been inhibited by cost compared to natural uranium fuel. Penalties include more complex logistics that

are required by the fuel's radioactive profile, which includes decay of some plutonium into americium (a neutron poison that emits gamma radiation). MOX fuel has been produced at an industrial scale in Belgium, France, and the UK, but it is likely that only France will make MOX fuel for LWRs during the 2020s, joined perhaps by Japan. Russia will make MOX fuel for fast reactors only.

China could, in principle, replicate and build on the experience of these, but it has far to go. China elected to begin operating the CEFR initially with HEU metal fuel provided by Russia, followed by eventual loading of MOX fuel, which would also be used for follow-on Chinese breeder reactors prior to an anticipated transition to metallic fuel.

In 2013, consultants told the Chinese government that China was decades behind other countries in establishing the technical basis for a nuclear power closed fuel cycle.¹⁵⁵ For political reasons, China could not implement a 2010 bilateral agreement with Belgium to replicate its MOX fuel know-how.¹⁵⁶ Without it, China is relying on laboratory equipment installed in 2003, comprising twelve glove boxes and Chinese-made equipment for mixing uranium and plutonium powder, compacting the powder into fuel pellets, and sintering the pellets. This plant was supposed to produce MOX fuel for the CEFR beginning in 2010.¹⁵⁷ As of early 2017, China has not loaded any MOX fuel into a PWR, and it has used very little, if any, in the CEFR. The small scale of China's MOX fuel fabrication line makes it difficult to assure homogeneity in a large batch.¹⁵⁸ To operate a 600-MWe breeder using MOX fuel, CNNC would need a license to build a MOX fuel fabrication plant with a design throughput of 20 MT/y.¹⁵⁹

Beyond challenges related to MOX fuel, China's transition from oxide to metallic fuel for fast reactors might begin around 2030 with an initial fabrication capacity for zirconium-plutonium-uranium fuel of 6 MT/y, about a decade after China sets up a pilot fabrication facility for this fuel.¹⁶⁰ Under GNEP, China pursued collaboration with U.S. national laboratories in this direction.¹⁶¹ Following from China's November 2016 bilateral nuclear cooperation agreement with Russia, it is possible that the two countries may cooperate to develop metallic fuel for China's fast reactor program. In principle, China could also cooperate with U.S. industry and laboratories interested in the development of metallic nuclear fuel.

Aqueous Fast Reactor Spent Fuel Reprocessing

There are considerable differences between the reprocessing of spent LWR fuel made of uranium oxide and the reprocessing of MOX fuel or metallic fuel that has been irradiated in fast reactors. The plutonium in fast reactor spent fuel can account for between 25 percent and 30 percent of the heavy metal content, compared to less than 2 percent in spent LWR fuel.¹⁶²

Reprocessing fast reactor fuel is beset with a number of specific challenges. High-burnup oxide fuel with high concentrations of plutonium is kinetically and thermodynamically more

difficult to dissolve, and the plutonium chemistry interferes with solvent extraction. These fuels can form cruds of noble metal alloys that do not dissolve. Likewise, plutonium-rich particulates from broken up spent fuel may emulsify and pose the threat of a criticality accident. At the laboratory scale, the danger of a serious criticality accident can be far more easily managed than in an industrial-scale installation holding bulk amounts of plutonium. The higher the burnup, the more difficult managing these issues can become. If highly radioactive matter remains undissolved during the initial processing stage, the heat it emits can damage plant equipment if particulates accumulate downstream. Not removing metal cruds will also reduce the efficiency of chemical separation.¹⁶³

Compared to LWR fuels, fast reactor spent fuels also exhibit a higher concentration of fission products. Most can be removed during product purification, but some highly radioactive elements are more difficult to remove. Finally, care must be taken to manage a higher level of solvent degradation during the reprocessing of spent fast reactor fuel, as well as the threat that organic materials requiring removal from the process stream may form explosive nitrate compounds; this problem has caused accidents in Russia and the United States.¹⁶⁴

A limited amount of fast reactor fuel with high plutonium content has been reprocessed in France, the United States, India, Germany, Japan, and Russia. All these countries but Russia used roughly the same chemical process. R&D on fast reactor fuel reprocessing may have accelerated over the last decade in response to GNEP and GIF international programs. Ongoing work includes developing processes that go beyond PUREX chemistry. As with pyroprocessing, the major challenge for aqueous reprocessing of fast reactor fuel will be to arrive at an industrial-scale process that is economical, efficient, and reliable.

Several decades of work may be necessary to reach that goal and, so far, China has little or no direct experience in reprocessing fast reactor spent fuel. China might instead focus on non-PUREX-type fast reactor reprocessing systems, especially pyroprocessing. But this technique, too, is far from being ready to deploy to treat large amounts of spent fast reactor fuel. In recent years China has foreseen possible construction of a plant to reprocess spent MOX fuel with a capacity of 50 MT/y to match the requirement for the 600-MWe breeder reactor now under construction.¹⁶⁵

Recycling of Reprocessed Uranium

In addition to plutonium, China also aims to reprocess spent fuel to recover uranium.

Reprocessing spent LWR fuel recovers both plutonium and uranium. Beginning four decades ago, a number of nuclear power-generating countries experimented with recycling reprocessed uranium (REPU) in their reactors. The amounts of REPU have been growing in step with the amount of spent fuel that has been reprocessed. As of about 2010, the total amount worldwide is estimated to be in the tens of thousands of metric tons.¹⁶⁶ However, the amount of

REPU that is recycled is relatively modest. Most is stored, but its use as nuclear reactor fuel—including at an industrial scale in LWRs—has been technically demonstrated. Because REPU contains isotopes that are neutron poisons and emit high levels of gamma radiation, however, use of the material as a commercial fuel raises its effective cost, especially for reactor owners that want to increase the level of fuel burnup. Most countries, therefore, do not aggressively recycle their REPU but consider it to be a future potential asset that would appreciate in value should the price of uranium increase relative to REPU processing and storage costs. For many years, the behavior of reactor owners concerning use of their REPU has been opportunistic: interest in recycling REPU appears positively correlated with concern about the security of uranium supply.¹⁶⁷

For decades, China made no firm plans to use REPU in its nuclear power program pending the introduction of spent fuel reprocessing.¹⁶⁸ In September 2016, leading Chinese nuclear firms signed a memorandum of understanding with Canadian counterparts to design, market, and build a 700-MWe power reactor intended to use REPU as fuel. The reactor design would be a more advanced version of a standard pressurized, heavy-water-moderated-and-cooled power reactor built in Canada and elsewhere, including two units operating in China since the 2000s. According to the Canadian vendor, China would build an initial two reactors; each would use the REPU recovered from the reprocessing of spent fuel from four Chinese PWRs.¹⁶⁹ Chinese experts expect that the foreseen commercial contracts for this project will include transfer of the ownership of technology for these reactor systems to China.¹⁷⁰ Officials close to this project said in 2016 that the spent REPU burned in the Canadian reactors would eventually be used as fuel for one or more Chinese fast reactors, pending the establishment of industrial-scale technology in China for the reprocessing of this spent fuel.¹⁷¹

High-Level Waste Disposal

Regardless of whether China elects to reprocess its PWR spent fuel, it will need to dispose of HLW. China's nuclear waste repository program resembles programs in other countries. Policymaking for nuclear waste disposal is in the hands of central government bodies: NSSA is the regulator, CNNC is designated as responsible for constructing and managing the repository, and a scientific body, the Beijing Research Institute of Uranium Geology, is in charge of project-related R&D. So far, China has conceived of the project to permit the repository to accept both spent fuel assemblies as well as vitrified reprocessing wastes, from both defense and civilian activities. The basic concept is that waste packages will be disposed of in horizontal shafts connected to tunnels bored into the repository site.

In 2003, after canvassing several possible locations in China for a repository, the government began focusing efforts to establish a geological repository for this waste in granite medium at Beishan in Gansu Province, a remote territory near the Jiuquan complex. During the 2000s,

China set 2020 as the target for finishing the conceptual design for the repository.¹⁷² In 2012, after the United States decided to abandon its Yucca Mountain project to dispose of power reactor spent fuel, China expanded the site selection for its future HLW repository to a total of twelve candidate sites. Clay was added to granite as a possible repository medium, and a decision on site selection was foreseen in 2020.¹⁷³

Before repository construction for the selected site can be licensed, China must finish a program of borehole testing, site selection, geological surveys, and studies on groundwater and radionuclide behavior in disposal media. China must also select a source for the bentonite rock that has been selected as a buffer medium for the repository. China plans to technically characterize waste packages, demonstrate the disposal technology, and build a site-specific underground laboratory sometime after 2020.¹⁷⁴ Until the repository is constructed and licensed to accept spent fuel, vitrified reprocessing HLW, and other forms of HLW, China can be expected to store all spent fuel and vitrified waste for an interim period.

OTHER NUCLEAR POWER TECHNOLOGIES

In addition to fast reactors and their associated fuel cycle technologies, China has invested in other nuclear technologies that could be deployed at a future time for power generation. The designs offer a variety of advantages, including passive safety features, deployment versatility, waste reduction, and lower coolant pressure. All of these reactor types would require the development of specific nuclear fuel management and/or processing technologies. Especially should China halt or slow down the forced development of fast reactors and reprocessing in the near term, China's nuclear technology focus in the 2020s and beyond may change and evolve, as new technologies emerge and attract interest while other avenues currently being pursued lose traction for technology-driven, political, and economic reasons. In recent years, Chinese R&D organizations and industry have prominently invested in the following future options.

Molten Salt Reactor

China initiated an R&D project during the 1970s to develop a molten salt reactor (MSR) but it made little progress for many years because potentially showstopping materials challenges quickly arose.¹⁷⁵ Beginning in 2011, CAS, which had been initially involved in the MSR exploration, resumed R&D in this field. It currently sponsors a project led by the Shanghai Institute of Applied Physics. If successful, this project will design and build a number of small experimental and pilot units over the next two to three decades, beginning with a pebble-bed reactor that operates on an open fuel cycle using solid fuel. Far more challenging are Chinese aspirations to develop and deploy liquid-fueled reactors that breed uranium-233 from thorium and operate on a closed fuel cycle. In any case, project officials caution that it may take

until 2035 or later before a Chinese MSR would possibly operate for industrial-scale power generation.¹⁷⁶

The MSR is a design that uses molten salt as the reactor coolant. The reactor operates at atmospheric pressure (sparing the technical and safety issues that derive from the enormous pressures reached in LWR systems), but at a higher temperature than LWRs, about 700 degrees Celsius. There are two design concepts, one based on solid fuel and the other on liquid fuel—China is interested in both. For the solid fuel design, which calls for tiny fuel pebbles, the salt is comparatively easy to handle using reactor equipment made of standard stainless steels. For the liquid fuel concept, there are complex corrosion challenges related to molten salt.

The MSR's attributes and challenges will not allow it to replace the LWR at any foreseeable future time. CAS is focused instead on smaller, modular units that may be appropriate for power generation and would include a turbine generator requiring no coolant water.¹⁷⁷ The MSR might, therefore, eventually be suitable for deployment in less-developed and drier regions in central and western China where, in the aftermath of the Fukushima accident, concern has been voiced that not enough local water would be available to assure safe LWR operation.

The CAS-sponsored group is beginning with a comparatively simple pebble-bed, solid-fueled reactor. A waste form for a once-through fuel cycle for this reactor is currently being studied. Unresolved issues concerning a liquid-fueled MSR are far more complex. Before such a reactor could be licensed, much work is needed concerning environmental impact; reactions involving molten salt; and pyroprocessing of the spent fuel and cleaning of the molten salt inventory in the reactor. It is not certain to Chinese experts how waste from a liquid-fueled reactor with a closed fuel cycle would be managed. Should China solve that problem inside two decades, the MSR may have a future impact on the direction of China's fast reactor R&D, with a design that can burn actinides from spent LWR fuel. But Chinese scientists caution that, even if successful, a thorium/uranium-fueled MSR design may not be in a position by 2050 to rival the population of LWRs and perhaps fast reactors operating on uranium/plutonium fuels—any contribution the MSR would make in this area would be additive.¹⁷⁸

The CAS group envisages the MSR to load thorium in the molten salt and breed uranium-233 by neutron capture. The fissionable uranium that is created and meant to be recycled would be separated by on-line pyroprocessing—a technique that poses considerable difficulties for separating uranium from thorium, including for reasons of chemistry, radiation resistance, compactness, exclusion of reactor moderator agents, compatibility with the molten salt carrier, and nonproliferation.¹⁷⁹ For the Chinese MSR project, a pyroprocessing scheme has yet to be technically conceptualized.¹⁸⁰

ADS and Thorium

China is also interested in developing a so-called Accelerator-Driven System (ADS) using a powerful particle accelerator to transmute actinides and breed uranium-233 in a thorium blanket that would undergo fission and generate power. In principle, the high-energy neutrons generated in a particle accelerator by bombarding target materials could be fired at other targets such as actinides.

ADS was included in China's National Basic Research Program (the so-called 973 Program) in 1999 after initial studies were carried out between 1996 and 1999. CIAE and the China Institute of High Energy Physics (IHEP) carried out a five-year program on the physics and technology for ADS, and then built an experimental platform. According to one IHEP scientist in 2011, China is "still in the phase of basic research and pre-research for key components" of ADS.¹⁸¹ He said that China will launch a three-phase project, beginning with a ten-year effort to build a high-power accelerator and associated test equipment, followed by construction of a prototype ADS and a 30-MWe reactor and initial transmutation experiments by 2035, and finally building a "full-size industrial demonstration 800-MWe power reactor driven by a 10-MWe beam accelerator" before 2050. Achieving this program, he said, "will take thirty years."¹⁸²

More recently, the project timetable for this project has been shortened to allow for completion of a demonstration facility by 2032, including a reactor with a rating of over 1,000 megawatts of thermal energy (MWt) capable of generating electricity and processing nuclear power spent fuel and/or HLW. The challenges are daunting and include the target material, the reactor blanket, waste separation, accelerator engineering, and ensuring system reliability at an industrial scale. In March 2016, CAS and nuclear power plant owner CGN—which aims to challenge CNNC's effective spent nuclear fuel processing monopoly—announced an agreement to cooperate in this field.¹⁸³

According to CAS scientists, currently there is "no existing model in the world" for what China is trying to accomplish on ADS.¹⁸⁴ China is not alone in researching ADS for power applications but the results concerning industrial applications have so far been modest. Accelerators have been designed that operate at only a small fraction of the beam strength necessary to build and operate an ADS functioning as a commercial-scale power reactor.¹⁸⁵ Other countries are continuing with ADS research that has been underway for several decades. Norway, which has large thorium reserves, has been doing thorium-plutonium fuel research for power applications. It concluded in 2008 that industrial application of thorium-based fuel cycle technology including ADS might well be possible in coming decades, but warned that substantial resources (measured in billions of U.S. dollars) would have to be invested to overcome economic disincentives and technical challenges.¹⁸⁶

Alternative Fast Reactor Designs

As part of the CAS ADS project, China is pursuing research on a lead-cooled fast reactor. CAS has proposed this type of reactor as the reference reactor for a Chinese ADS system, in three consecutive phases: 1) design of a 10-MWt research reactor by about 2020; 2) development of a 100-MWt experimental reactor during the 2020s; and 3) development of a 1,000-MWt demonstration reactor through the end of the 2030s. Until now, China's lead-cooled reactor activities have not been prioritized on par with sodium-cooled fast reactor development.

In 2006, U.S.-based company TerraPower launched an initiative to license and build a proposed so-called traveling wave reactor. The initial version of the reactor called for a core of HEU fuel to undergo fission in a "traveling wave" pattern from top to bottom over a period of several decades, during which time all the fuel would remain in the core; thereafter, it would be removed and disposed of in a repository. The concept was intended to address concerns that spent fuel from conventional reactors, including fast reactors, would be a source of plutonium that could be diverted for nuclear weapons. In 2010, facing licensing difficulties in the United States and searching for a location with required infrastructure to prove that the reactor design was feasible, the company focused its attention on setting up a project in China with the cooperation of Chinese industry and government and supported by the U.S. government.

Since then, TerraPower has significantly altered its reactor concept following discussions with China's nuclear industry to accommodate the limitations of current technologies, including with respect to materials requirements, possible know-how classification issues in the United States, and the engineering preferences of Chinese organizations.¹⁸⁷ In 2015, TerraPower and CNNC agreed on the outlines of a project to build a reactor in cooperation with China's fast reactor program. The arrangement would call for CIAE to develop the fuel and the reactor core for a pool-type 600-MWe power reactor, for which CNNC would be architect and engineer.¹⁸⁸

This proposed reactor is a sodium-cooled fast reactor that would initially operate using driver fuel assemblies containing enriched uranium that breed plutonium in a uranium-238 blanket surrounding the core. The reactor would be shut down for one to two weeks per year to shuffle fuel assemblies to optimize operating and safety conditions. The core of the reactor would be replaced every ten years. The irradiated fuel removed from the core is to be re-clad and reused to drive up to three more reactors. The reactor concept would result in less spent fuel than would be generated in an LWR and, according to TerraPower, the spent fuel would be disposed of in a repository rather than reprocessed.¹⁸⁹ TerraPower says that the reactor system is designed to use either depleted uranium or natural uranium but, in principle, it could also use spent PWR fuel in the future.¹⁹⁰

The project draws upon the experience of fast reactor technology development in the United States. Some U.S. experts said that if the project goes forward in the near term, licensing may pose a challenge because there are no international design review criteria. As discussed above, some unofficial reports since 2015 speculated that the TerraPower project would be sited at Xiapu in Fujian Province and built after the CFR-600.¹⁹¹

High-Temperature, Gas-Cooled Reactor

Beginning in 1986, China's 863 Program included the development of a high-temperature gas-cooled reactor (HTGR) for power generation and process heat applications. On the basis of technology acquired from Germany—including spherical fuel element production—Tsinghua University in 2012 began operating a small pilot high-temperature reactor, HTR-10, north of Beijing. This was followed by an ambitious project to set up a series of twenty bigger modular units to demonstrate the HTGR's viability for large-scale power generation.

A two-module HTGR-based power plant has been under construction at the Shidaowan site in Shandong Province since 2012. Each module is rated at 250 MWt for a combined power rating of 211 MWe. The project includes technology holder Tsinghua University, general contractor Chinergy, and investor Huaneng, a Chinese utility company. Huaneng abandoned the plan to build twenty HTGR units in Shandong in favor of a new plan to build a six-module station that would be rated at 655 MWe. Officials close to China's HTGR program said in 2017 that the costs for the 20-unit project were unfavorable compared to PWR costs in China. Huaneng is now building a PWR at the Shandong site.

Like the MSR, the HTGR is still a niche technology facing scaling-up challenges during development. Even if successful, it might not significantly contribute to China's electric power production for perhaps two decades or more. The further development of the HTGR may be discouraged if China decides to support only nuclear power systems including a closed fuel cycle.¹⁹² Until now, no plans have been made for the reprocessing of spent HTGR fuel in China. Chemical reprocessing of HTGR spent fuel is technically feasible but there is no industrial-scale technology established for this.

More Water-Cooled Reactors

Under China's 973 Program, a number of universities and industry R&D outlets are working on the development of a so-called supercritical water-cooled reactor (SCWR) that would operate above the critical pressure for water. If successful, the design would allow for higher thermal efficiency than offered by current LWRs, and a simplification of plant design because water flow rates would be lower and no steam-related equipment (steam generator, steam dryers, or coolant recirculation system) would be necessary. The engineering would rely on advanced technology for supercritical coal-burning power plants that China has already

mastered. China is actively cooperating in the GIF program on this research, with the goal of producing the finished design for a 1,000-MWe reactor that could be constructed during the 2020s. The SCWR's fuel cycle options would be the same as for China's LWRs.

The SCWR has an advantage over other reactors being pursued because it is a water-cooled and water-moderated reactor and thus represents a straightforward evolution from the LWR. But the concept faces challenges in safety-system design and qualification, fuel cladding materials, and heat-transfer technologies, in part related to the reactor's higher operating temperature and pressure.

Separately, China continues to research and develop PWRs in parallel with its steadily increasing capacity to build and operate these reactors. The support of government policymakers to encourage R&D on fast reactors has not deterred Chinese industry from remaining primarily focused on PWRs. These firms invested heavily in the capacity to build up to ten PWRs annually, and they are counting on central planners to permit them to continue building these reactors in the coming decades. To date, the central government has not announced specific goals for new PWR projects beyond 2020, but the Thirteenth Five-Year Plan includes preparation to start more reactor construction before 2020 and the Fourteenth Five-Year Plan includes additional preparation for an initial eight reactors.¹⁹³ Regardless of the ambitions of fast reactor advocates to begin phasing out PWRs in favor of fast reactors by mid-century, most external industry officials queried said they expect that China will continue to favor building PWRs because that's what its nuclear engineering sector knows best. Some executives from Chinese reactor-owning firms said in 2017 that, regardless of the development of fast reactor systems, they were confident that the PWR would remain China's leading power reactor technology throughout this century.

In recent years, the government encouraged CNNC and CGN to combine forces to arrive at a unified design for a 1,000-MWe PWR that China could export beginning in the 2020s. That reactor, Hualong-1 or HPR-1000, is an amalgam of two separate versions of foreign (mostly French) PWR technology that the two companies independently built in series since the 1990s. In the wake of Westinghouse's difficulties launching its AP1000 PWR in China, it is possible that Hualong-1, or a bigger version of the design, may become China's standard PWR sometime during the 2020s.

Finally, China is developing small and medium-sized reactors (SMRs) for power generation for specific applications including marine vessels and off-shore and remote terrestrial locations. These include a 125-MWe PWR design that would serve as the basis for a 100-MWe "floating" nuclear power station.¹⁹⁴ SMRs, including HTGRs, may be favored in China to produce electricity for future synergetic hybrid systems relying on both nuclear and renewables, to replace coal-fired capacity, and for deployment in arid regions. These units might be built in factories and then shipped to designated sites for erection.

CONTROLLED NUCLEAR FUSION REACTOR

The three-step nuclear power development strategy proposed for China foresees that, beginning in the 2020s, the country will deploy nuclear fusion reactors, inaugurating the beginning of a third stage of nuclear power development intended to take place between 2050 and 2100 following the industrial-scale deployment of both PWRs and fast reactors.

A fusion power plant would get its energy from the fusion of nuclei of two hydrogen isotopes, deuterium and tritium, to form helium, thereby releasing neutrons and a great quantity of energy. There are two basic approaches: Magnetic fusion aims to heat hydrogen gas that is injected into a cage, to a temperature of about 100 million degrees Celsius, and sustain the reaction using magnetic fields. Inertial confinement fusion attempts to fuse nuclear materials using lasers. China is currently pursuing both avenues.

China began research into magnetic nuclear fusion energy in 1958, but the work was sidetracked in favor of efforts to build nuclear weapons. After China successfully tested a nuclear fission explosive device in 1964, it very quickly moved toward the development of nuclear fusion weapons. China established the capability to produce and work with fusion energy materials—chiefly lithium-6, deuterium, and lithium-6 deuteride—and successfully tested a thermonuclear weapon in 1967.¹⁹⁵

The magnetic fusion project got back on track after 1973 and, since then, has been greatly enlarged to include numerous research institutes.¹⁹⁶ Funding is mostly provided through CAS, the Ministry of Education, and China's military procurement agency, which has been part of the Ministry of Industry and Information Technology since 2008.¹⁹⁷

During the last two decades, China has set up magnetic fusion facilities including several tokamaks—large magnetic confinement devices to contain hot plasma and produce fusion energy. Today, China is part of the international ITER project to demonstrate the engineering feasibility of the system and show that it is possible to produce energy-yielding plasma. ITER aims to complete this project by about 2025. According to one Chinese fusion scientist, entry into the ITER project was of “strategic importance” for China because it should “raise China's nuclear fusion technology to the international level” and “lay a foundation for China to independently carry out the R&D for a nuclear fusion demonstration power station.”

The first step would be a 500-MWt experimental fusion reactor that Chinese researchers want to construct and operate by 2035. Between 2036 and 2050, under the ITER program, China would have two options: to build a 1-GW fusion-fission demonstration reactor and then “commercialize fusion energy,” or instead build a 1-GW magnetic confinement fusion demonstration reactor for energy applications.¹⁹⁸ These schedules are consistent with the timetable for China's three-step nuclear energy development scenario. Scientists say that magnetic fusion would not simply succeed nuclear fission energy production during the

second half of the century. Instead, between 2020 and 2050, experimental and demonstration reactors would be designed and operated to breed nuclear fission materials and to transmute high-level waste from fission nuclear power plants.¹⁹⁹

The technical challenges and investment requirements standing in the way of controlled fusion power generation are severe enough to have prompted a number of scientists at CAS to formally object in 2005 to the Chinese government's decision to fund a dedicated magnetic fusion research project. Unresolved issues include the search for materials that will resist neutron bombardment and confine the radioactivity generated by neutrons as well as radioactive dust and tritium gas. Equipment in a large nuclear fusion reactor for power generation would be subject to extreme mechanical stress and high heat.

Separately, Chinese universities, one of which is affiliated with China's nuclear weapons program, are pursuing R&D on inertial confinement fusion, which aims to use high-intensity lasers to eventually generate fusion energy for industrial and commercial applications, including power generation. Chinese researchers have developed a group of high-intensity laser drivers to compress target material, with the aim of demonstrating ignition of a target by around 2020.²⁰⁰ If China succeeds, it will enter a narrow field of countries with significant R&D programs that are working on inertial confinement fusion. Several countries have demonstrated ignition of targets, but none has quite yet achieved the high-energy gains needed as a prerequisite to demonstrate industrial and commercial viability. Technical and economic challenges are formidable and construction of industrial-scale inertial confinement fusion reactors to generate electricity may be at least several decades away. It may prove difficult to design and operate a fusion reactor based on pulse-delivering lasers in a truly continuous mode with the high reliability that would be essential for electricity production.

STRATEGIC TAKEAWAYS

When China dramatically accelerated its nuclear power program in 2005, it provided a long-term strategic narrative projecting that current technologies would be replaced by two advanced nuclear systems: the fast reactor and the nuclear fusion reactor. China would generate nuclear power for centuries.

In 2005, China was not at the forefront of most of the nuclear technologies it selected for future development. Since then, China has prioritized deployment of PWRs but also intensified support for R&D on fast reactors, nuclear fusion, other fission reactor types, and reprocessing, with the aim of catching up to foreign nuclear programs.

Previous efforts elsewhere to commercialize the fast reactor ran aground on technical and economic difficulties—these might also confound China. Although it can build on post-1990s

technical progress in international fast reactor R&D, China is still at a comparatively early stage in areas like fuel processing and fabrication.

China has a mixed record in meeting its nuclear deployment planning goals. It has completed many PWR projects on time, but it has cut back capacity plans that were accelerated in 2005. It has not met timetables in medium- to long-term plans for fast reactors, advanced fuel development, and reprocessing, though these timetables appear intended to be approximate or, as Chinese planners say, “flexible.” China’s failure to meet projected deployment timetables may reflect insufficient political commitment, inadequate financing, and/or technological difficulties. In looking ahead to future endeavors, it should be noted that China currently has comparatively little experience in many of its target areas for nuclear development.

Approaching 2020, Beijing’s plan for nuclear power development, set forth in the 1980s and provided with a timetable in 2005, will be at a technology crossroads. China will have to answer these questions:

- What criteria should China use to decide whether and how to fund advanced nuclear technology development projects? How much should China invest in a future closed fuel cycle, including technologies such as P&T and pyroprocessing that may be critical to China’s long-term nuclear power generation but may not be ripe for industrial-scale deployment for two or more decades?
- Will China’s decisions to support advanced nuclear technologies reduce its commitment to PWR development and safety, putting its PWR infrastructure at risk toward the second half of the century?
- Is China prepared to force the pace of advanced nuclear technology industrial projects regardless of its relative lack of experience in critical areas? Does China’s success in replicating existing PWR technology imply that China will innovate in the development of advanced technology?
- How should China engage foreign governments and industry in the 2020s in pursuit of advanced nuclear technologies? What would a near-term decision by China to deploy a joint prototype industrial fast reactor with U.S. partners imply about the future of its CNNC-centered and, until now, Russian-based fast reactor development program?
- On what basis will China select the most promising advanced nuclear power technologies from those that it is currently funding and politically supporting? How will China make decisions and organize the transition from R&D to industrial-scale and commercial deployment for these technologies?

ELECTRICITY POLICY AND ECONOMICS

The future of nuclear power is uncertain. The structure of many countries' electricity sectors initially favored investments in nuclear power but has evolved to discourage them. Given these current conditions, it is not certain that the world's nuclear industry will be economically viable through the middle of this century. More than any other power-generation technology option, nuclear power requires a long-term commitment from governments, investors, and publics for it to be used safely and in a sustainable manner. In part to recover rising capital costs, future nuclear power plants will be designed to have operating lifetimes of sixty years or more, and expenses related to planning, licensing, decommissioning, and waste management will extend the life cycle of a nuclear project to a century or even longer.

In general, greater uncertainty about the future of nuclear power implies greater perception of risk. This may deter governments and industries from investing in more advanced and expensive nuclear technologies, particularly those requiring long lead times for R&D and industrial demonstration, and especially if decisionmakers are not confident that these investments will result in commercially exploitable assets based on sound technology that can be further developed.

When most of the world's nuclear power plants were built, governments considered electricity supply, transmission, and distribution to be a natural monopoly, due to the lack of competition resulting from fixed costs to new entrants. They viewed the high capital investment costs

prevailing in the electric power sector as an insurmountable barrier that would prevent new entrants from competing with an established single provider that would enjoy a lower average cost and economies of scale for the production of a public good. Companies in the business of producing electricity invested in nuclear power because the cost would be borne by consumers and reflected in the rate base.

Since the 1990s, many governments have deregulated their electricity sectors to encourage competition. This sometimes implied that the price for nuclear power must be increased compared to other sources for producers to make a profit, and, in most markets, it meant that new nuclear power investments would be more expensive than alternative technologies. In addition, some governments have introduced policy measures that subsidize the development and deployment of selected non-nuclear technologies to generate electricity.

China quickly and impressively assimilated proven foreign know-how to build initial LWRs and then replicate them under tight construction schedules and with few delays. But how quickly will China move forward this century with the advanced nuclear technologies discussed in the last chapter? The realization of the CEFR pilot project required nearly twenty-five years. On the basis of their previous experience, experts who were involved in fast reactor programs in Europe, Japan, and Russia cautioned during workshops in May 2015 and June 2016 that China should not expect to design, build, and operate a commercial demonstration fast reactor without significant delays.²⁰¹ More broadly, these experts underscored that current multilateral international efforts in support of fast reactor development are beset with the formidable challenge of transitioning from fast reactor R&D programs to deploying commercially viable nuclear systems.²⁰²

Given this background, it is important for policymakers and investors alike to consider whether the economic and electricity policy environments in China will indefinitely favor nuclear power and, beyond that, support efforts to deploy more advanced nuclear systems with a different risk profile that may require greater financial and political commitment.

NUCLEAR ECONOMICS IN CHINA BEFORE 2005

Beginning in the late 1970s, China planned to introduce nuclear electricity to its mix of power sources having concluded that the cost would be justified by the value of the investment. This conclusion was backed by a number of Chinese studies, which argued that nuclear power would be cost-competitive with other sources.²⁰³ From the beginning of China's nuclear power program, the central government—like governments in other countries that had decided in favor of nuclear power a decade or two before—firmly controlled its electricity sector and was responsible for making all investment and most pricing decisions.

A few skeptics argued then that the high capital cost of nuclear power plants would deter China from investing in renewable energy sources and that nuclear power would not compete with the cheap and available coal resources that supplied about three-quarters of China's power.²⁰⁴ But the central government's decision to build a small number of nuclear power plants was based on political, energy security, and technology policy rationales, largely independent of cost considerations, that emerged out of China's post-Cultural Revolution reform process.

As Deng Xiaoping's economic modernization led to higher growth, Beijing began reforming China's electricity sector to incentivize greater power production, including making allowance for both foreign capital financing and broader Chinese investment in nuclear power projects. During the 1980s and 1990s, whether China could afford nuclear power mattered less because most of the nuclear power plants were built under contracts concluded for equipment and services provided by foreign vendor companies. The financing for these projects was underwritten by foreign governments on behalf of their industries. Indeed, between 1980 and 1996, the Chinese state's contribution to the financing of power sector investments fell from 60 percent to 0.2 percent, while foreign contributions increased from zero to 12 percent.²⁰⁵ Diversification of investment and decentralization of production was encouraged by spectacular economic growth along China's seaboard—particularly in Guangdong Province, where restive political and industrial leaders were keen to challenge Beijing's claim to sole decisionmaking authority.²⁰⁶

Economic considerations about nuclear power arose more distinctly during the 2000s, after China's leaders decided to dramatically accelerate the pace of nuclear power plant investment, in the shadow of coal supply bottlenecks and as demand for electricity continued to increase. Coal shortfalls were accompanied by an increase in coal prices and Chinese coal imports that the government interpreted as a long-term future trend, leading planners to predict that nuclear power would by itself become comparatively more competitive against coal in the future.²⁰⁷ As coal prices and imports rose, state-owned power companies piled up debt and ran losses, and they successfully lobbied the government to permit them to invest in nuclear power. Beijing agreed. In the aftermath of the central government's 2005 decision to speed up nuclear power development, a nuclear gold rush occurred: SOEs carved out of the former state energy ministry as part of ongoing electricity sector reform placed their bets on government planners' long-term projections of electricity demand growth, and they formed partnerships with local and provincial governments to propose scores of nuclear power plant projects all over China.²⁰⁸

CHINESE GOVERNMENT ASSISTANCE FOR NUCLEAR POWER

The nuclear power plants China built over the ensuing decade turned out to be very profitable. During the period 2002 through 2012, China's two nuclear power generators, CGN

and CNNC, recorded annual returns against assets of 7.1 percent, more than double the levels attained during those years by thermal power plant companies.²⁰⁹ The concerns of these firms' government shareholders about project risk were assuaged by expectations that nuclear projects would hold their own against coal and renewables because they would be located close to their markets: densely populated seaboard areas that were experiencing high economic growth. Provincial governments' political resistance against transboundary power sales, and the daunting task facing China's grid companies to move electricity across long distances, provided still more insurance for nuclear investment projects located along China's eastern coastline.

Then and now, the profitability of Chinese nuclear investments has benefited from the support of provincial and central government leaders. This assistance is provided in a number of ways, most significant of which are:

Access to Information and Decisionmakers

The number of corporate entities allowed to invest in the nuclear power sector is strictly limited; all firms are owned and controlled by the state. The Communist Party, the most powerful organization in China, is involved in all top-level personnel decisions. Senior SOE managers in the power sector are promoted into central and provincial governments, where they "retain their links to the companies and provide insights from and arguments favorable to the companies."²¹⁰ Nearly all high-ranking government officials are members of the Communist Party and subject to its discipline. SOEs have a Communist Party hierarchy parallel to the management hierarchy, in which the party secretary may have more authority than senior managers.²¹¹ Management's access to the Communist Party is influential and can facilitate support from local and provincial industry and governments, including for pre-authorization infrastructural work to support construction of projects in advance of formal approval by the State Council and other regulators. Many or even most of China's proposed nuclear construction projects may have benefitted in this way.²¹² More generally, lack of accountability and transparency in decisionmaking on energy-related issues has, for decades and until recently, been fostered by the relatively underdeveloped status of China's legal system and civil society.²¹³ This has meant, in practice, that price setting and dispatching policies are subject to ad hoc, crisis-management decisionmaking, where opaque political influence and personal relationships may strongly factor.²¹⁴ That said, it is also true that since the late 1990s, corporatization of China's electricity industry—including its nuclear SOEs—has to a certain extent challenged the power of the Communist Party and the Chinese state to direct firms to make nuclear asset management and investment decisions. To a greater degree than before, leaders of China's nuclear SOEs in recent years have encouraged the development of a management culture that distinguishes the interests of the companies from those of the Chinese state and the Communist Party.

Financial Subsidies

Power-generating SOEs have not been obligated until recently to pay dividends to their government shareholders. So-called policy banks, such as the China Development Bank, have provided these companies, above all CNNC, loans at favorable, state-subsidized rates.²¹⁵ More generally, the SOEs benefit from controls on deposit interest rates that permit state-owned lenders to provide nuclear-project financing at selected low discount rates that give nuclear power a clear and very large financing cost advantage.²¹⁶

Favorable Price Setting

Perhaps the most effective potential financial perk that the Chinese state affords nuclear power is the arrangement of favorable price conditions to deliver nuclear-generated electricity to the grid. China's central planning agency, NDRC, controls the price at which power producers sell their output. It sets a different feed-in tariff for each power source: nuclear, solar, wind, hydro, and coal. For as long as the central government has taken this approach, the guaranteed tariff paid to producers for nuclear power—0.43 renminbi per kilowatt-hour (RMB/kWh) in 2016 and 2017—has been higher than the rate for either coal-fired or hydroelectric power, in part reflecting higher capital costs for nuclear plants.²¹⁷ How important to the welfare of China's nuclear sector is this remunerative tariff? "We watch this carefully," said one Chinese nuclear industry executive in 2015. "If the government were to take this away from us, the future of our business would be in a lot of trouble."²¹⁸

ELECTRICITY SECTOR REFORM AND NUCLEAR POWER

Electricity reform in China began modestly nearly fifty years ago but it has been ongoing and it will likely continue. The more profound and effective China's electricity sector reform is, the more economics and cost considerations will factor in future nuclear policy decisionmaking.

ELECTRICITY MARKET REFORM

Following government decentralization initiatives in the 1980s and 1990s, Beijing began commercializing and unbundling the power sector. Many of the steps China took during the early 2000s looked familiar to government officials and company executives who were deregulating power systems in Western countries.

China's State Planning Commission, the central government's mammoth planning agency, was rebranded as NDRC in 2003. It established a central government Energy Bureau, which later was upgraded to a vice-ministerial National Energy Administration, or NEA. The state created a Ministry of Environmental Protection (MEP), and then set up the State-Owned Asset Supervision and Administration Commission (SASAC), which assumed the role of

central government shareholder for power sector SOEs. The central government also made an attempt to set up a power industry regulatory commission.

In parallel, China's leadership took actions to expose its electric power system to market forces. This process began in 2002, when Beijing unbundled the gigantic China State Power Corporation (SPC), which owned most of China's transmission and distribution infrastructure and a large share of China's generation capacity. In the wake of the breakup, two grid-management companies were set up that would be independent of five new power-generating SOEs that were also hived off of SPC. These five companies acquired nearly half of China's electric power generating capacity within five years.²¹⁹ This drive was fueled by the 2005 central government decision to accelerate nuclear power plant construction discussed above. Power-generating SOEs successfully pressured the government to allow them to raise capital in the bond market to finance their forthcoming nuclear capacity investments in line with the central government's now-higher reactor-building targets.

Power generators were especially inclined to invest in nuclear power plants for two reasons: 1) rising prices for domestic coal, which—beginning in the mid-2000s, in the wake of coal sector reforms—were tracking international market prices; and 2) the absence of an effective mechanism that linked the price of coal to the on-grid price of thermal power.²²⁰ In this situation, it was only a matter of time before industry firms began pressing the government for a more fundamental reform of its price-setting system. Today, this reform is still at an early stage and, in the view of Chinese market advocates, it has far to go. Whereas until the 2000s China's nuclear sector was too small to influence the state's price setting, that situation changed as more and more reactors were built. Since 2005, NDRC has assured that nuclear power generators benefit from higher tariffs for the power they sell to the grid.

In the coming years under Xi Jinping, two important power reform agenda items may profoundly affect the nuclear sector: Beijing's long term ambition to introduce market mechanisms, and its even-more-ambitious effort to decarbonize China's electricity generation system. Both these interests strongly figured in Xi's 2014 proclamation of a "revolution in energy production and consumption" that would cut back waste, incentivize investment in non-fossil energy sources, enlarge the role of market forces, and reform energy sector regulations and governance.²²¹ The future of NDRC's tariff setting, including for nuclear power, is at the heart of both initiatives.

ENVIRONMENTAL POLICY-DRIVEN MEASURES AND GROWTH

As evidenced, deployment of nuclear power generation technology in China was informed from the outset by the need to diversify away from coal. China's resolve to decarbonize its power sector has intensified in response to certainty among experts worldwide that atmospheric carbon dioxide emissions must be dramatically reduced to avoid adverse global

climate change, but, until now, China's need to reduce particulate air pollution has been the primary environmental policy driver for nuclear power.

In 2009, China announced that it aimed by 2020 to reduce CO₂ emissions intensity (average emissions per unit of gross domestic product) by 40–45 percent below the 2005 level and to increase the share of non-fossil fuels in primary energy production by 2020 to 15 percent.²²² In 2016, China ratified the agreement forged at the United Nations climate change conference in Paris on carbon reductions that would limit anticipated global temperature increases. In doing this, China extended the horizon of its climate mitigation commitments beyond 2020 to 2030, and agreed to reduce its CO₂ emissions intensity by 60–65 percent and increase the non-fossil share of energy production to 20 percent, implying a peaking of China's CO₂ emissions by 2030. These goals were also reflected in climate policy targets included in China's Thirteenth Five-Year Plan (2016–2020).²²³ Under five-year plans covering 2011 through 2020, China has been aggressively expanding investment in power production capacity from wind, solar, and nuclear sources. If goals are met, China's capacity for wind-powered power generation will have increased from 31 GWe in 2010 to 200 GWe in 2020; solar-powered capacity will have increased from about 1 GWe in 2010 to 70 GWe in 2020; and nuclear power capacity will increase to 58 GWe in 2020 with an additional 30 GWe under construction.

What NDRC's planning targets imply for the period after 2020 is not spelled out, and this is subject to conjecture and wishful thinking by participants and observers who favor (or not) the deployment of specific power generation technologies. The amount of nuclear power that will be allocated in future five-year plans will depend, *inter alia*, upon: expectations for economic growth, government carbon-reduction goals and commitments, and technology development including for electricity storage and carbon sequestration as well as power generation. It will also depend on the architecture of the power system—in particular, whether Chinese power demand will indefinitely include a substantial base load that would be served by nuclear power plants, as has been the case so far, and how deeply ultra-high-voltage transmission infrastructure in the future penetrates the Chinese power grid.

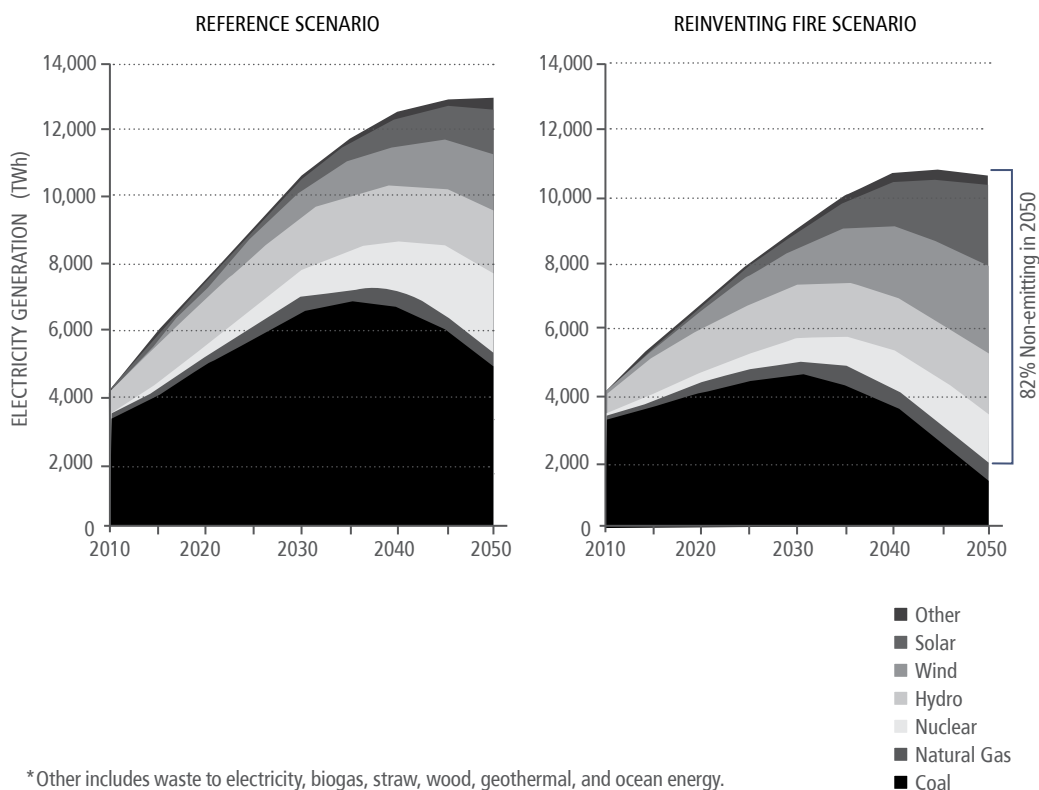
Especially prior to the Fukushima accident, some quasi-official Chinese government agency estimates for nuclear power installed capacity in 2050 were as high as 400–500 GWe. These estimates corresponded to numbers used by scientists at the Lawrence Berkeley National Laboratory (LBNL) in the United States beginning during the late 2000s, in cooperation with researchers affiliated with NDRC, which used Chinese data to model future projected Chinese electricity demand and greenhouse gas emissions.²²⁴

Barring unforeseen developments, Chinese government planners and research organizations are not expecting that the evolution of China's power system by 2050 will warrant any decisionmaking that would halt the continued incremental growth in nuclear power—generating

capacity. But during the course of the 2010s, projections for future nuclear capacity growth in China have, on balance, dipped sharply lower. This, in part, reflects caution after the severe nuclear accident in Japan in 2011, as well as the expectations for lower economic and power demand growth termed China’s “new normal” by Xi and other Chinese officials since 2014.

Current and persisting “new normal” and environmental imperatives in China’s political economy do not imply that China will turn away from nuclear power by mid-century. Notably, a computer model—developed by a non-governmental research organization critical of nuclear energy and that advocates aggressive energy efficiency policies and renewables build-out in China—has projected that, under a scenario highly favorable to carbon emissions reductions, to maximize reductions China will continue increasing its installed nuclear power capacity to about 180 GWe by 2050. This is less than half of some optimistic pre-Fukushima estimates but it is still twice the amount of nuclear capacity that China expects to have in place by 2025 under the Thirteenth Five-Year Plan, and approaching twice the nuclear capacity of the current nuclear capacity in the United States.

PROJECTED CHINESE POWER SOURCES TO 2050



*Other includes waste to electricity, biogas, straw, wood, geothermal, and ocean energy.

Source: Rocky Mountain Institute, *Reinventing Fire: China* team analysis.

Projections by these researchers for Chinese power production in the upper right viewgraph thus anticipate that nuclear power will be a significant component in a climate-favorable power generation mix that would be 82 percent non-carbon-emitting in 2050. This projection is very optimistic and, according to its authors, will not come about without a massive cumulative investment of \$5.2 trillion (RMB 35 trillion).²²⁵ What in fact transpires through 2050 might differ from these projections to the extent that events are adversely (from the point of decarbonization) influenced by a number of factors including: the capabilities of China's labor force; whether China invests heavily in cheap natural gas; whether China follows its conventional growth model favoring capital goods investment and construction; whether technical barriers prevent further development of low-carbon technologies; how politicians and planners balance high-penetration renewables in the Chinese power planning system; and whether SOEs are subject to reforms.²²⁶

The scenario in the left viewgraph, featuring less conservation and more coal and nuclear power generation, reflects more conventional Chinese reference assumptions and data from NDRC's Energy Research Institute (ERI), which collaborated with LBNL. In fact, these experts' upper and lower bounds for projected electricity generation through 2050 are consistent with a number of other recent projections, such as those made by the International Energy Agency.²²⁷ To meet this level of demand, some researchers estimate that, by 2030, China's grid will likely add 1,000–2,000 GWe in generating capacity, and that, in order to also meet targets China set in 2016 for climate mitigation, 900 GWe of that added capacity must be non-fossil generating capacity—beyond investments covered in the Thirteenth Five-Year Plan. If so, Chinese researchers collaborating with LBNL say that most of the non-fossil capacity additions “will be renewables [and/] or nuclear.”²²⁸ More generally, new nuclear capacity will continue to be added, a Chinese electricity planning official said in 2016, “so long China is committed to decarbonize and as long as NDRC and NEA anticipate that renewables penetration in China will be limited to between 20 percent and 30 percent of China's total power supply.”²²⁹

Demographic and geographic aspects will also be critical to the future of China's nuclear power expansion. So far, all of China's nuclear power plants have been built along the country's densely populated eastern seaboard. Researchers in 2015 concluded, however, that these high-income areas are experiencing a leveling off of per capita power consumption, and they caution that “the relationship between per capita electricity consumption and economic development is evolving to a new stage, and that per capita electricity demand is growing only moderately in most Chinese provinces, or even plateauing in the most developed regions, with the exception of a few energy extractive provinces.”²³⁰ According to Chinese nuclear industry officials in 2015, projections for continued expansion in nuclear power capacity beyond 100 GWe are based on the expectation that previously foreseen projects for construction of nuclear power plants on sites in inland China will be carried out.²³¹ But in the wake of the

Fukushima accident, the Chinese government has been reluctant to implement these plans made during the 2000s. Without inland nuclear projects coming on line, a nuclear generating capacity for China greater than 100–150 MWe by 2050 might not materialize.

Provided that recent expectations for future power demand are accurate, China's national carbon emissions reduction goals and commitment to the Paris agreement may justify adding a few hundred GWe in additional installed nuclear generating capacity between 2020 and 2030 alone. But actual capacity addition would be subject to numerous constraints, including the future development of power demand under the so-called new normal conditions and possible related political constraints.

If China, in the coming years, prioritizes adding non-fossil generating capacity, nuclear additions may be favored if other non-emitting technologies encounter difficulties. Since the early 2010s, uncoordinated investment in wind machines that increased capacity annually by 60 percent has led to high curtailment rates. The addition of large amounts of intermittent power has also severely challenged the government's dispatching and pricing system, designed for fixed quotas and fixed prices unrelated to supply and demand. Increasing movements of power through the system are putting China's dispatching and pricing mechanisms under more and more pressure.²³² This pressure may increase in response to Xi's announcements in 2015 and 2016 that the government aims to introduce competitive dispatching.²³³

Another factor that cannot be ignored by policymakers considering the future prospects for China's nuclear power sector is the sheer size and clout of China's coal sector. Thirty-thousand coal mines employ six million workers. Regardless of central government efforts to cut back, coal production increased from 1 billion short tons to nearly 4 billion short tons between 2000 and 2014. Local and provincial politicians who support the coal industry frequently ignore central government directives. When Beijing orders local and provincial governments to shutter plants, closings are delayed and plants are often restarted as soon as coal prices rise. Investment in new projects goes ahead regardless of excess capacity and in defiance of orders to cut coal production. There is pressure along the entire supply chain: coal mines, generating stations, and engineering and construction firms. Local protests by coal workers are routine, and the potential for unrest may temper Beijing's resolve to wind down China's coal industry. On the other side of the ledger are perhaps 700 million urban Chinese who expect the state and the Communist Party to deliver clean air. Until and perhaps after coal emissions peak around 2030, the government will be politically challenged by this dilemma.

FUTURE NUCLEAR COSTS

Chinese decisionmakers' efforts to substitute nuclear for coal-fired power will be still more difficult because nuclear power in China is expensive. In regions where the coal industry is powerful, coal-fired power producers enjoy considerable cost advantages over their nuclear

competitors. Regions with big surplus coal-fired generating capacity are putting base load electricity on the grid at discount prices—for example, 0.3538 RMB/kWh in Shanxi and 0.2937 RMB/kWh in Neiming. These prices are, respectively, 20 percent and 33 percent below the guaranteed support price for nuclear power.²³⁴

In recent years, the combination of lower growth rates for both GDP and power demand, comparatively high costs for nuclear power, and political pressures from coal and renewables have led to curtailments in the nuclear power sector. The result has been lower load factors for Chinese nuclear power plants, and pressure from the government on nuclear generators to operate reactors under load-following regimes, a state of affairs that would result in still-higher nuclear power production costs.²³⁵ These pressures on costs may increase in the coming years, especially if China adds generating capacity to the grid at rates that are considerably higher than current and projected rates of power demand.²³⁶ Should this current situation persist, conflict between the nuclear industry and government market reformers will certainly escalate, especially over how the government prioritizes dispatching of renewables, nuclear, and hydroelectric power sources.

Far from headlines with official boasts about new records for China's ever-growing installed nuclear capacity, data made available to Chinese media in March 2017 underscored the potential threat to nuclear power economics posed by reduced plant availability. According to Chinese nuclear utility executives, a nuclear power plant in China must be operated for about 7,000 hours per year to service the loans that financed the project. Beginning in 2015, in some regions where nuclear power capacity has been steadily built up, availability has dropped to 5,000 hours per year.²³⁷

Furthermore, buyers of cheap coal-fired power in the future may pay even less because of falling transmission charges (as low as 0.10-0.15 RMB/kWh over distances as long as 2,000 kilometers, or about 1,242 miles), as the highly corporatized China State Grid Corporation (CSGC) moves forward with record ultra-high-voltage power line investments. For 2016 alone, CSGC, the world's largest and most cash-rich power transmission and distribution company, allocated about \$86 billion (RMB 543 billion) for new investments.²³⁸

During most of the last decade, coal-fired power plants in east coast areas where power reactors are located have been producing electricity at prices close to the high nuclear off-take price. But with more and more power transmitted to the coast from the far-flung mine-mouth coal-fired stations and intermittent sources that are favored by Chinese environmental laws, east coast nuclear power prices may come under still greater pressure. Nuclear investments could be stranded if decisionmakers in Beijing and powerful CSGC break down the political barriers across the country that still inhibit the sale and transmission of electricity across provincial boundaries.

Whether recent local and regional trends toward a decline in nuclear power production become generalized will depend on how the state balances the interests of the different participants who sell their power to the grid. Just over a decade after Wen Jiabao ushered in a nuclear construction bonanza, potential investors today—and perhaps for years to come—can no longer assume that new nuclear power plants in China come with a license to print money.

The more China catches up with the West, the more its economy will lose competitive advantage based on low costs of basic factor inputs. Thanks in large part to inefficient dispatching, capacity overbuilding, lack of transparency in pricing, and selective protectionism, electric power in China today may cost 30 percent more on average than in the United States.²³⁹ Given that nuclear power in China has always been more expensive than coal-fired power, if the Chinese government aims to defend the economy's international comparative advantage, it will seek to control or even to lower the cost of nuclear power.

Unless the government is willing to underwrite more expensive nuclear power production for long-term strategic reasons, cost will be a factor in any decisions made by the government and SOEs on whether to shift investment from PWR-based nuclear power plants toward one-off or limited-series commercial-scale fast reactors and related nuclear fuel cycle infrastructure.

What has happened in China's HTGR program suggests that a decision by the government in favor of such technology-driven investments is not a foregone conclusion. Last decade, China launched a project to build ten twin-unit 105-MWe HTGR power plants, a total of twenty reactors, in series at the Shidaowan site in Shandong Province. Like the fast reactor, the HTGR was designated a strategic technology in 1986 by central planners. But the HTGR project in Shidaowan will be halted after the first pair of units is completed in 2018. According to officials from the project's consortium, the generation cost (in part based on the project cost) for these units was found during project implementation to be 25 percent higher than for a Chinese PWR-based power station.²⁴⁰ Utility investors are now planning on building a large PWR on the site instead. The HTGR program will be redesigned for lower construction and procurement costs, and it is foreseen that the next HTGR project will be a 655-MWe station consisting of six modules linked to one turbine generator, intended to reap greater economies of scale.²⁴¹ Even for a reactor model that the government had favored since 1986 for strategic reasons, comparative costs matter to state-owned investors.

FAST REACTOR COSTS

The lessons from China's HTGR program should be transferable to other nuclear investment projects. Compared to China's PWRs, costs for design engineering, licensing, procurement, and installation will be higher for a prototype or demonstration fast reactor because it will be unique. Operations costs are a function of reliability; what can be expected for a new industrial prototype or demonstration fast reactor is difficult to predict. Compared to LWRs,

which provide potential investors a database of about 14,000 years of cumulative commercial operation, the world's fast reactors have compiled a total experience of just a few hundred years.²⁴² Demonstration units in Japan, the UK, and the United States experienced prolonged shutdowns, and the lifetime capacity of France's first industrial-scale fast reactor over a ten-year period was just 7 percent.²⁴³ On the other hand, two units—Phénix in France and BN-600 in Russia—eventually operated for 151 and 165 consecutive days, respectively. A follow-on commercial-scale French reactor operated successfully throughout 1996, generating more electricity than during its previous nine years of operation, before it was ordered shut by a French government programmatically opposed to continuing the project.²⁴⁴ For future prototype or demonstration fast reactors to succeed, investors need to tolerate that they may have to operate long enough to benefit from a learning curve.

In the wake of France's experience with fast reactor development over half a century, national utility company *Électricité de France* will not commit itself to the construction of a commercial fast reactor without remedial attention being paid to specific technical issues that previously limited reliability, including aerosol deposits, corrosion, and sodium containment integrity. Engineering changes in some previously operating units permitted these reactors to, at times, attain availability factors of between 50 percent and 80 percent. But, according to a senior expert in France's fast reactor program, "to be competitive with other generating systems, a reliability factor higher than 90% will be necessary. Innovations in materials must impact favorably on refueling outages, maintenance, and in-service inspections, lengthen component lifetimes... Industrial application of materials advances should make sure that sodium leaks are very rare events; design of circuits and equipment must permit repair or replacement with a very short delay or a few days."²⁴⁵

Japanese experts likewise concluded, on the basis of experience from Japan's fast reactor program, that future reactors must address capacity factor, capital cost, and fuel cost. To lower costs, plant life must be extended from forty to sixty years; reactor systems must be simplified; advanced codes and standards must be used during construction; maintenance periods must be shortened; fuel burnup must be increased; and the operating cycle length between inspection and refueling outages must be lengthened to two years.²⁴⁶

China's nuclear industry executives say they expect that the government will pay the extra cost for fast reactors if their investment and operating costs exceed costs of PWRs.²⁴⁷ Based on China's experience in cost management for the CEFBR, industry also expects that construction and power generation expenses for a demonstration breeder reactor would be higher than for a Chinese PWR. This view is consistent with the experience of fast reactor experts in Western Europe, Japan, Russia, and the United States queried by the author in 2015 and 2016. Most experts concurred that, overall, the costs related to any new demonstration fast reactor would be higher than for a PWR.²⁴⁸ Chinese sources likewise suggested that investors from the Three

Gorges hydroelectric project, who may be willing to support construction of a demonstration fast reactor in Fujian Province, would likely be assured in advance by the government that this unique and strategic-designated project would benefit from government subsidies and/or that the effective feed-in tariff governing power sales from the fast reactor to the grid would be higher than for all other nuclear power reactors—regardless of the interest of NDRC planners under Xi to reduce market distortions in China's price-setting system.

The CEFR, according to CIAE, cost \$387 million (RMB 2.5 billion)—if so, that was a bargain by today's nuclear plant costs but nearly four times more than was budgeted a quarter century earlier, when the project got underway with a budget of \$106 million (RMB 680 million). CIAE blamed lack of experience in design engineering and construction, especially for pool-type reactors, for a large share of the overrun. CIAE had to make expensive design changes in major components and, because the Chinese government (in CIAE's view) did not adequately support the project; the 39 percent share of project costs represented by procurement was lower than for China's PWRs (although low procurement share reduced the project price compared to PWRs).²⁴⁹ CIAE bought and then modified the project to incorporate equipment from Italy's discontinued fast reactor project, and supply of equipment from Russian partners in the project was delayed by political turmoil after the collapse of the Soviet Union; these developments increased costs.²⁵⁰ CIAE aims to make a number of improvements to lower project costs for its 600-MWe fast reactor. These concern, *inter alia*, engineering design procedures and core design, fuel burnup, steam generators, overall heat efficiency, and more efficient use of construction materials—all issues that contributed to higher CEFR project costs.²⁵¹

REPROCESSING COSTS

In contrast to cost components for future fast reactors, the costs associated with the investment and operation of bulk reprocessing plants based on PUREX chemistry have been studied at length and are better understood, especially because the reprocessing of spent fuel using this technology has been an established commercial activity for several decades.²⁵² Chinese officials in 2013 told the author that media reports asserting that French vendor Areva had offered to build an 800 MTHM/y reprocessing plant in China for about EUR 20 billion were credible.²⁵³ This price was also in line with the cost for a similar, nearly completed plant built by Areva in Japan, which Japanese industry stated in 2007 was 2.2 trillion yen.²⁵⁴

No public cost data is available for the 200 MTHM/y reprocessing plant that China is building at Jinta, but it can be assumed that this expense would be considerably less than for an Areva-supplied plant because, as was the case for the CEFR, a large share of the design engineering, construction, and procurement will be domestically sourced.²⁵⁵ Low cost estimates for this project may have afforded China leverage to persuade Areva to reduce its price for the 800 MTHM/y reprocessing plant by about EUR 5 billion.²⁵⁶

In advance of a decision to build and operate an industrial-scale facility for reprocessing large amounts of spent PWR fuel, Chinese executives in 2015 and 2016 told the author that there was then no agreement between China's two largest reactor owners, CGN and CNNC, about how to proceed. Because CNNC has been delegated overall responsibility for developing and managing the back end of China's nuclear fuel cycle industry, SPIC and CGN officials have voiced concern that these firms will be commercially disadvantaged and "overcharged" by CNNC for reprocessing services.²⁵⁷ CNNC may view future reprocessing revenue from captive clients as a way to recoup lower margins it faces in some other civilian and defense-related nuclear business activities.²⁵⁸ The government and CNNC would have several options to raise money for a reprocessing plant investment, including direct financing, soft loans, and recourse to a spent fuel management fund derived by tax revenue levied on all operating reactors in China at a rate of 2.6 Chinese cents per kilowatt-hour (U.S. 0.38 cent/kWh). CGN, which is critical of CNNC's reprocessing monopoly, advised NDRC in 2013 that the proceeds from the fund won't suffice to pay for reprocessing.²⁵⁹

On the basis of data available for existing and previous reprocessing programs, external researchers have generally concluded that the cost of reprocessing in China would exceed the cost of dry-storing China's spent fuel.²⁶⁰ Researchers at Harvard University estimate the cost of reprocessing spent fuel for such a plant to be between \$1,000/kg and \$5,600/kg, relying upon other projections for capital cost, interest, decommissioning, capacity factor, and operation.²⁶¹ In response, Chinese sources have claimed that the low figure is closer to what has been expressed in official Chinese data through 2013 based on expectations, including for interest rates, about how the government and CNNC would finance a large reprocessing plant project.²⁶² The higher numbers in the Harvard study, Chinese officials assert, are more consistent with industry expectations for higher factor costs in Western nuclear power programs, such as those included as historical references in the study. In any case, should China choose to invest in an industrial closed nuclear fuel cycle, in addition to the above expense for aqueous reprocessing of spent PWR fuel, it would face costs associated with the production of plutonium fuel (MOX fuel and/or metallic fuel) and waste management, including disposal, along with the appropriate costs for uranium procurement, uranium conversion and enrichment, fabrication of uranium-oxide fuel, dry storage of spent fuel and—for fast reactors—higher costs than obtain for PWRs related to fuel fabrication and spent fuel reprocessing.

Researchers' conclusions that the cost of nuclear power in China would be higher with a closed fuel cycle are consistent with results of a number of economic studies for other nuclear programs carried out since the 1990s. Depending on assumptions by researchers in these studies, the share of fuel cycle costs associated with reprocessing and recycling of nuclear fuel may be between 14 percent and 66 percent.²⁶³ For most nuclear power-generating countries, the prospect of considerably higher costs would deter investors and governments from committing to an industrial closed nuclear fuel cycle. Informed by an understanding that the fuel

cycle cost component associated with managing spent nuclear fuel represents a relatively small fraction of the total levelized cost of electricity generation (according to the Organization for Economic Cooperation and Development [OECD]/NEA perhaps between 2 percent and 4 percent), China may develop confidence that these higher costs would be compensated for by strategic benefits.²⁶⁴

STRATEGIC TAKEAWAYS

Economics is increasingly significant to China's nuclear power program. In the future, the more China's economy resembles the economies of other advanced nuclear countries, the more economics will factor into decisionmaking.

Like many other nuclear power countries, China was initially undeterred by nuclear costs because its electricity sector was fully integrated and its initial nuclear power plants were financed by foreign vendors and their governments. Beijing favored nuclear power in line with policy goals—technology development, energy security, and pollution reduction—that were independent of cost consideration.

Nuclear costs became a factor in decisionmaking beginning in the 2000s, after Beijing launched electricity sector reforms while accelerating nuclear power plant deployment and corporatizing its power industry to raise more funds for electric power investments.

Today, China's nuclear power industry is challenged by Beijing's conflicting electricity policy goals of increasing market transparency while maintaining dirigiste control. After Beijing unbundled transmission and distribution from power generation, nuclear SOEs needed protection from the state to sell their electricity to the grid at a price that guaranteed sufficient revenue to service their growing debt. These perquisites are the lifeline for China's nuclear power industry, and they would be threatened by market forces that China's leadership might unleash in their continuing efforts to influence decisions on new capacity investment and lower costs.

Downward pressure on favorable nuclear feed-in tariffs may arise from a shift in China's growth model, national grid unification, falling marginal power demand, and decisionmaking by corporatized SOEs that departs from the state's strategic interests. The worst-case economic scenario for nuclear power in China is that nuclear power plants become stranded investments because so-called new normal conditions persist and electricity reform continues in the absence of correctives by the state.

Anticipated economic trends in the 2020s will not favor China transitioning to more advanced nuclear technology and a closed nuclear fuel cycle. The more China compels its electricity sector to lower overall system costs, the more the state will be under pressure to monetize and subsidize the cost of nuclear power's assumed noncommercial strategic benefits.

OTHER ISSUES CRITICAL TO CHINESE DECISIONMAKING

Decisionmaking about nuclear power is, to a great extent, about harnessing the technology and industrial resources discussed in the first three chapters of this report. But several other issues with strategic implications will also be critical, not only to the technological direction of China's nuclear program but also concerning China's future participation in international trade and global nuclear governance.

ENERGY SECURITY

From the outset, China's technocrats and political leaders who embarked on nuclear power development took for granted that the state was obligated to provide for a sufficient and reliable energy supply. Reflecting conventional wisdom in foreign nuclear programs, beginning in the 1980s, Chinese decisionmakers were warned that China would run out of uranium unless they took steps to close the nuclear fuel cycle. In 2007, three years after premier Wen Jiabao dramatically increased the pace of reactor building, scientists at CIAE proposed that China undertake a radical transition from PWRs to fast breeder reactors, proposing that fast reactors account for 80 percent of China's nuclear capacity by 2050. Should China continue to operate only PWRs, a leading CIAE scientist said that, in sixty years, China would need a supply of uranium equivalent to about half of the world's uranium resources.²⁶⁵

China has good reasons to be concerned about energy security. During the last three decades of uninterrupted high economic growth, China's welfare has come to depend on a reliable and increasing supply of energy. In line with the rise of annual per capita GDP in China from about \$100 in 1980 to about \$7,000 in 2017, China's annual per capita consumption of energy during the same period has increased from 600 kilograms to 2,000 kilograms of oil equivalent. The trend line in the electricity sector is similar. In 1990, China consumed just one-fifth of the amount of electric power consumed in the United States; by 2013, China led the world in electricity consumption, exceeding the second-place United States by 25 percent.²⁶⁶

China's leaders, energy experts, and media in recent years have raised the profile of energy security as a national policy concern. They have focused most of their attention upon China's supply of petroleum, which accounts for 20 percent of China's total primary energy consumption. After decades of self-sufficiency, China is now a net importer of ever-larger quantities of oil and currently relies upon foreign sources to meet 60 percent of its requirements. Some experts forecast that China's dependency may increase to about 75 percent by 2030. Similar concerns have been raised about China's rising imports of natural gas.²⁶⁷

Rising dependence upon foreign sources of oil and gas has raised awareness about energy security, but these fuels generate little electricity in China. Far more significant to the power sector is China's conventional expectation that more and more uranium will be required to decarbonize China's power system before the end of this century and, beyond that, serve as a major electricity fuel well into the twenty-second century. As is also the case for fossil fuels, the domestic supply of uranium is limited, and China expects to rely on external sources to meet most of its future uranium needs in the near to medium term.

From the outset of China's nuclear power program and until the mid-2000s, when it began ramping up nuclear power plant construction, China's demand for uranium closely tracked its domestic uranium production. Thereafter, China's uranium deficit—the amount China annually required over and above what it mined and milled domestically—steadily increased to reach about 2,600 metric tons of uranium (MTU) in 2016.²⁶⁸ China's demand for uranium will continue to increase steadily. China may require 10,100–12,000 MTU in 2020, 12,300–16,200 MTU in 2030, and 14,400–20,500 MTU in 2035.²⁶⁹ China expects to meet this demand using three sources: domestic production, overseas resources, and market purchases. Domestic production will likely account for the smallest share of the increase. More will be supplied from overseas resources tapped as a result of Chinese foreign investment, and the largest share may derive from open-market purchases.²⁷⁰ In the near term, China expects to import increasingly large amounts of uranium from Kazakhstan and Namibia, among other sources where Chinese companies have made investments and secured contracts.

In anticipation of its growing future needs, China has been stockpiling uranium since the 2000s. As of 2015, China's inventory approached 85,000 MTU of uranium, which is equal to 140 percent of total annual global uranium demand or about ten years' of then-current Chinese requirements.²⁷¹ This implied that China was buying about one-quarter of the uranium available on the world market.²⁷² Should, in the coming decades, China expand its nuclear capacity to 150 GWe, China's requirement might grow to about 25,000 MTU per year (MTU/y) if all of its reactors were fueled with fresh uranium.²⁷³ This would be about 40 percent of the world's current uranium output of about 62,000 MTU/y, according to the World Nuclear Association, an industry organization.

Could world uranium production expand in the 2020s and 2030s to accommodate significantly greater Chinese demand? According to OECD and IAEA tracking of the global uranium market, the answer is probably yes. Their unlikely high-growth scenario for nuclear power through 2035, projecting a total world installed capacity of 683 GWe, would require about 105,000 MTU/y—nearly double current production. To meet that level of demand through 2035, they conclude, the world's current resource base would be “more than adequate.”

Should Chinese nuclear power plant owners continue indefinitely stockpiling uranium to fulfill ten forward years of requirements, they would need to accumulate a running inventory of about 250,000 MTU of uranium to match an installed nuclear generating capacity of 150 GWe. Such an inventory would likely represent somewhat more than three times the annual world uranium production sufficient to meet the fuel requirements for the IAEA's projected low-growth nuclear power scenario for 2035 (installed capacity of 418 GWe) or perhaps about twice the world annual uranium production needed under the IAEA's high-growth scenario. That rate of accumulation also implies that China would annually be buying about twice the amount of uranium that it buys now.

Whether the world will produce enough uranium to permit China such an inventory is an open question. From the perspective of Chinese government and industry, the security of China's future uranium supply will depend on how autonomous China's leaders believe the country must be. Should China adopt a more relaxed view on international nuclear cooperation, China “will shift from a high inventory strategy to being comfortable with lower inventories.”²⁷⁴ Other experts suggest that China's current stockpiling might not be strictly intentional but instead the consequence of a post-Fukushima slowdown in China's reactor construction, and/or a Chinese policy to commoditize its current account surpluses as an alternative to holding U.S. government debt. In any case, if China's behavior eventually reflects international practice, its uranium stockpiling will decline. Chinese customs data show that the trend line of Chinese uranium imports during the last ten years has been upward and exceeds \$2 billion a year, though it may have stabilized as of 2016.²⁷⁵

According to the OECD/IAEA, current global uranium resources would suffice for 160 years if the 2017 worldwide level of uranium demand were to remain indefinitely constant. Beyond this, “exploitation of the entire current conventional resource base”—including speculative reserves—“would increase this to well over 240 years” provided, however, that “significantly increased demand and market prices” would incentivize additional uranium exploration and resource development.²⁷⁶ In general, the uranium industry is confident that the positive historical correlation between expenditure on uranium exploration and production and the size of the conventional uranium resource base will continue to be valid, implying that more and more uranium-laden resources will be identified as investment in uranium production increases. During the last decade, China has become a very major player in the global uranium market. This position will give China market power that it should be able to wield to its advantage to obtain large amounts of uranium under comparatively favorable commercial conditions.

NUCLEAR WEAPONS, NONPROLIFERATION, AND NUCLEAR SECURITY

China is a party to the NPT and is recognized by the treaty as one of five states legitimately possessing nuclear weapons, having detonated a nuclear explosive device four years before the NPT’s deadline on January 1, 1968.

China was the last of the NPT nuclear-weapon states to develop a nuclear power infrastructure. In all cases and for many years, central government agencies administered development of both nuclear weapons and nuclear power-related activities, and industrial companies including state-owned enterprises were active in both military and civilian nuclear programs.

Nuclear energy technologies are dual-use technologies: China’s nuclear power program was launched by the central government in part to contribute to the downsizing of China’s military. Today, China’s nuclear R&D institutions, industry firms, academies, and universities train experts who may find employment in either civilian or military nuclear enterprises. As China’s investment in power-projecting technologies expands hand in hand with China’s growing political and economic might, Beijing will want to ensure that China has sufficient nuclear experts to manage and further develop its nuclear weapons assets. As is the case for other nuclear-armed powers, China’s investment in nuclear materials production, processing, and management—and specifically in advanced nuclear fuel cycle systems and reprocessing, uranium enrichment and other technologies for isotope separation—may both indirectly and directly contribute to its nuclear defense.

Like other NPT nuclear-weapon states, China is not obligated under the NPT to apply IAEA safeguards to any of its nuclear materials and activities.²⁷⁷ The NPT does, however, obligate China to not proliferate nuclear weapons to other countries. China, like other NPT parties,

must secure its nuclear materials to ensure that they are not lost, stolen, or diverted to non-peaceful uses outside of China.

Separate from its NPT commitments, China has nonproliferation and nuclear security–related obligations following from specific bilateral agreements with numerous countries including Australia, Canada, France, the UK, and the United States. These agreements were negotiated to facilitate nuclear cooperation, including commercial arrangements. Provisions in specific bilateral agreements obligate China to not use nuclear equipment, information, material, or technology provided by a foreign state for any military purpose; to facilitate bilateral verification of that obligation; and not to retransfer export-controlled items to third parties without prior consent. These agreements may include additional national security–related obligations that could have a bearing on China’s nuclear power and nuclear fuel cycle development.²⁷⁸

During an interagency review of the prospective sale of an Areva reprocessing plant to China, the French government considered the potential proliferation risks associated with that transaction. According to participants in those deliberations, it was concluded that Areva should not export a reprocessing plant to China using PUREX technology; that the facility should not be co-located on a military site such as Plant 404 at Jiuquan; and that IAEA safeguards should be applied to the installation.²⁷⁹ The European Commission has undertaken advance preparations to incorporate safeguards measures into the design of a reprocessing plant that Areva would build in China.

While knowledge and experience obtained through the development of reprocessing capabilities may contribute to China’s nuclear defense, U.S. government officials told the author in 2016 that the United States has little concern that reprocessing technology or equipment provided by Areva to China would be misappropriated to produce plutonium for China’s nuclear weapons program if the plant were not subject to IAEA safeguards.²⁸⁰ Consistent with that view, when the United States renewed its bilateral agreement for peaceful nuclear cooperation with China in 2015, it agreed to a new provision that provided China advance programmatic approval to reprocess U.S.-obligated spent fuel in China without IAEA safeguards.

At the same time, U.S. government officials publicly urged China not to reprocess its spent fuel and, according to European counterparts, they also urged France not to proceed with bilaterally negotiated arrangements supporting the transfer of an Areva reprocessing plant to China.²⁸¹ Some U.S. officials have claimed that Chinese reprocessing of power reactor spent fuel would encourage other states (especially Japan and South Korea) to separate plutonium from their spent power reactor fuel.²⁸²

It is not obvious that by reprocessing its power reactor spent fuel, China would precipitate a regional “plutonium competition.” Fuel-cycle policy in Japan and Korea has evolved in a similar fashion as China’s but over a longer trajectory. There is no evidence that China’s

nuclear activity has prompted decisionmaking by either Japan or South Korea about the future of their nuclear fuel cycles. Japan has reprocessed power reactor spent fuel since 1977 and a large-scale Areva reprocessing plant has been under construction in Japan since 1989. South Korea in 1997 launched a program to develop pyroprocessing technology to recover and recycle nuclear material from its spent power reactor fuel. From the inception of its nuclear weapons program, China has not relied on nuclear power–related activities to provide nuclear explosive materials for its nuclear defense.

China, in the future, may exceed the record of other advanced nuclear countries and effectively close its industrial nuclear fuel cycle using fast reactors, reprocessing, and nuclear fuel recycling. That might result in a global re-evaluation of nuclear power and an upturn in sensitive R&D and other activities that would raise proliferation concerns, including about the transfers of nuclear wares from states with advanced nuclear fuel cycle technology to states that do not have these capabilities, and about possible hedging behavior of some states. Since 2004, China has been a member of the Nuclear Suppliers Group (NSG), an association of forty-eight countries that regulate the world's nuclear trade. Specific conditions in the NSG's guidelines obligate members to restrain the transfer of sensitive nuclear fuel cycle technology.

Should China embark on an industrial-scale nuclear fuel cycle, the logistical challenge of managing large quantities of plutonium would raise nuclear security concerns. These have already factored in China's decisionmaking. During the 1980s, Chinese nuclear experts assumed that an industrial-scale reprocessing plant would be sited in remote western China, which already hosted sensitive defense nuclear activities. More recently, China's perspective has changed. In the aftermath of the September 11, 2001, attacks in the United States and amidst rising concern about separatist violence in western China, Beijing is systematically evaluating terrorist threats to transports of nuclear material. Today, in consideration of the logistical and security challenge of transporting large amounts of nuclear fuel to and from coastal nuclear power plant sites to remote inland processing locations, China is considering reprocessing spent nuclear fuel at one of several locations closer to its nuclear power plants.

Compared to other advanced nuclear power programs, little information is publicly available concerning the transport of nuclear materials inside China, making it more difficult for observers to assess the security challenges associated with a substantially larger future nuclear power program and a more complex nuclear fuel cycle. China's external uranium suppliers say that they have no direct information about where, how, and whether uranium is delivered to designated end-users once China takes custody; not all the uranium China imports is subject to peaceful-use commitments.²⁸³ China has numerous regulations in place, and has taken further actions, to secure nuclear materials in its civilian nuclear program.²⁸⁴ The record appears to be consistent with assertions, including during the Nuclear Security Summit process, that Beijing is mitigating nuclear security risks.

The security investment needed for a nuclear power program based on industrial-scale plutonium recycling with fast reactors will be far greater than Beijing's current requirements for securing low-enriched uranium and unprocessed spent fuel. Like other NPT nuclear-weapon states that have deployed reprocessing plants and fast reactors, China should be able to provide adequate physical protection and other nuclear security arrangements for a closed nuclear fuel cycle, especially if it is designed to consolidate sensitive nuclear materials and minimize their movements. The more nuclear materials are dispersed across China's territory—and the more they are exposed to human access during processing and transport—the greater the risk of misappropriation.

STRATEGIC TECHNOLOGY POLICY

Modernizers under Deng Xiaoping aimed to catch up with industrialized countries in the field of science and technology, and China for four decades has viewed nuclear energy as a critical field for development. The wealthier China became, the more money Beijing spent. Beginning in the mid-1980s, advanced nuclear power reactors and nuclear fuel processing installations were singled out as targets for strategic government investment.

When Beijing set up a National High Technology R&D Program in 1986 (the so-called 863 Program) to encourage civilian applications of military-directed know-how, it identified nuclear energy as a “key,” or “critical,” technology for China and earmarked development of a fast reactor that became the CEFR. Two decades later, Wen Jiabao's decision to ramp up nuclear construction coincided with the promulgation of a fifteen-year national Medium- and Long-Term Program for Science and Technology Development that, in effect, repackaged the 863 Program. It included three nuclear “megaprojects” for development of advanced PWRs, HTGRs, and a “large commercial spent fuel reprocessing demonstration project to achieve a closed fuel cycle.”²⁸⁵

In parallel, the government set up a funding program for basic scientific research, the so-called 973 Program, to serve a quarter-million scientists. In 2000, this program began funding ADS research and, in 2007, it provided more R&D funds directed toward partitioning and transmutation of spent fuel materials. The 973 Program has also funded two concepts for a supercritical water-cooled reactor: a mixed-spectrum reactor design involving eight R&D institutes, universities, and industrial firms; and a proposed 1,000-MWe reactor design.²⁸⁶

Specific R&D directives were also drafted in 2005 for a fifteen-year Medium- and Long-Term Plan for Nuclear Power Development. In November 2014, the State Council issued an Energy Development Action Plan for 2014–2020, announcing government funding support for “large PWRs”—including Chinese development of the CAP-1400 PWR based on the AP1000 Westinghouse design under construction in China since 2008—and for

development of the Hualong-1 PWR by CNNC and CGN. The plan also included funding for HTGRs and fast reactors. This directive underscored that, during the 2020s, “the PWR will be the leading reactor in China, but not the sole reactor type.”²⁸⁷

From the outset, a leading role in the Chinese government’s support for nuclear technology has fallen to CAS. It functions as an academic institution, think tank, organizer, and funder for nuclear research projects. In 2011, CAS took over ADS research from the 973 Program, including its half-billion-dollar budget to carry out the first phase of a three-phase project aiming to demonstrate partitioning and transmutation by 2032. CAS has also sponsored lead-cooled reactor research and, in 2011, added a long-trajectory program at the Shanghai Institute of Applied Physics to develop a thorium molten salt reactor.

But throwing money at big nuclear science projects is one thing while achieving success is another. The problems encountered by the CEFR suggest that the government’s commitment to fast reactor development wasn’t open-ended or even consistent. The 2016 decision to halt serial deployment of the HTGR at Shidaowan suggests that efforts to commercialize this technology may not have sufficiently considered the economic requirements of power-generating companies foreseen as prime future investors.

In 2015, CAS documented a raft of problems in China’s efforts to close the nuclear fuel cycle, after it was tasked by the government to assess R&D in this area. Despite visionaries’ expectations since the 1980s that a closed fuel cycle would materialize, CAS concluded that China was “twenty five years behind India” on reprocessing development; lacked a “unified leadership” to carry out a demonstration reprocessing plant project; was hindered by uncoordinated and decentralized management of spent fuel inventories; and had failed to develop a cadre of specialists, especially younger experts. What expertise and responsibilities in this field China had were scattered throughout numerous CNNC departments, military organizations, and universities. Compared to the industrial sector, compensation for specialists working in Chinese research organizations was found to be demotivating.²⁸⁸

Four decades after post-Mao modernizers raised the question whether China’s nuclear development should rely on indigenous R&D or foreign cooperation, it would appear the debate has not been fully settled. To be sure, China very successfully assimilated PWR technology transferred from foreign companies. But China’s nuclear power road map now calls on industry and government agencies to innovate and develop deployable advanced technology. Especially because government R&D programs were set up to reduce reliance on foreign technology in support of Chinese import substitution policies, CAS urged the government to reopen this question and “hold a scientific debate at the national level on the extremely costly purchase of reprocessing facilities from foreign firms” to consider “the wisdom of the wholesale introduction of the technology.”²⁸⁹

When China's 2006–2020 R&D plan was announced, its emphasis on “indigenous innovation” led some experts to conclude that “advocates of a strategic science and technology policy to strengthen indigenous R&D clearly have won out.”²⁹⁰ But as this plan nears its conclusion, questions loom about whether China can command nuclear innovation from the top down and ensure that successful industrial and commercial application will follow. For many years, reaching back to before the Cultural Revolution, China's industrial development has been inhibited by command economy–style separation of R&D and productive functions that resulted in little innovation.²⁹¹ On occasion, including in recent years under Xi, the state has admonished R&D organizations, such as CAS, to focus more on getting real-world results from funded research projects. CAS, in return, is not alone in identifying problems in China's state-directed and highly centralized approach to R&D, “especially in project initiation and design.”²⁹² Particularly if planners call for China's future nuclear development to increasingly rely on technologies without a proven industrial track record—where project risk will be difficult to assess and may, in some areas, be greater than for what is already deployed—it isn't clear that increasingly corporatized nuclear firms will simply carry out the will of the Chinese state and the Communist Party, unless they are assured that their costs and risks will be covered by the government. But the realities of China's so-called new normal, including rising debt and slower growth, suggest that SOEs in coming years might not be able to count upon Beijing to assume the risk that managers will fail.

These questions now beset R&D planners who will be expected to provide guidance when the current fifteen-year technology planning blueprints run their course in 2020. In advance, Xi has ordained that existing R&D programs, specifically 863 and 973, will be superseded by a new streamlined organization to “unify planning and assessment of major projects.” This organization will have five channels, one of which will be responsible for nuclear technology under “national science and technology major projects.”²⁹³

NUCLEAR SAFETY

Nuclear safety issues were not critical to government and industry decisionmaking for many years during China's nuclear energy development. China's first nuclear power plant, Qinshan-1, was built without controversy in the shadow of a debilitating severe accident at the Three Mile Island nuclear power plant in the United States. The Chernobyl accident likewise did not deter China from going forward with the deployment of Soviet-design nuclear power technology.

China's reaction was very different when three power reactors at Fukushima-Daiichi in Japan melted down in March 2011. Beijing instantly grasped that the implications for China's nuclear program were significant.

China had taken for granted that Japan would prevent or effectively mitigate a nuclear accident at a Japanese nuclear power plant, and assure that a severe core-damage event with off-site consequences would not happen. The failure of one of the world's most technologically equipped and experienced nuclear power-generating countries to do that immediately prompted questions by leaders in Beijing whether China, with far less experience than Japan, is vulnerable to a severe accident, including because of governance deficits. The prospect that unknown weaknesses may be lurking in China's nuclear safety culture was potentially alarming to the political leadership because, only a few years before, it had dramatically accelerated China's nuclear power development with the aim of eventually installing three or four times the number of nuclear power plants that were operating in Japan at the time of the Fukushima accident.

Within weeks after Fukushima, the State Council ordered safety reviews, suspended new construction, and then lowered the government's target for nuclear power capacity for 2020 from 70 GWe to 58 GWe, allowing for thirty reactors to be under construction.²⁹⁴ From that point forward, NEA and NDRC could no longer take for granted projections from industry and R&D organizations that China was on track to expand nuclear capacity toward 400–500 GWe by 2050. By 2012, Chinese industry and government officials were willing to openly warn that China's pre-Fukushima expectations for indefinite forced nuclear power expansion were too risky. In 2012, nuclear safety began to figure in the Chinese government's programmatic nuclear slogans. "Steady development with safety" became the official watchword for the Chinese population.²⁹⁵ In some cases, nuclear safety checks were prompted by non-nuclear industrial accidents in China that revealed woeful safety culture deficits.²⁹⁶

Until at least 2020, China will not license reactor construction on any of fifteen inland plant sites, a policy issued by the government in direct response to concerns about site suitability raised by nuclear critics after Fukushima. The main concern is that a severe accident at a nuclear power plant would lead to the contamination of rivers and ground water. This is being investigated by NNSA's technical support organization, but it may be difficult to resolve for lack of benchmarks. Executives at China's nuclear industry association, which has lobbied the government to approve construction at these sites, acknowledge that some of the proposed inland sites currently lack infrastructure and resources. Some Chinese industry experts say they advocate limiting inland nuclear plant construction to newer-design reactors deemed safer than most of China's PWRs. During internal discussions with government agencies, proponents of alternatives to PWRs have claimed that their designs are inherently safer than the PWR—assertions that could prove misleading and counterproductive should they be debated by a Chinese public that has little information and knowledge about nuclear matters.

Foreign governments and industry firms questioned during the 2000s whether China's nuclear regulatory and safety regime would keep abreast of Beijing's aggressive reactor construction.

A 2010 IAEA peer review of China's nuclear regulatory system urged China to provide NNSA with more money and more personnel, and to ensure that policies and laws "keep pace with China's nuclear development program."²⁹⁷ At this time, Western governments believed that NNSA had little bureaucratic weight, and they raised concerns that NNSA could not enforce quality standards for equipment and procedures because it could not compete with SOEs for staff, money, and influence.²⁹⁸ Foreign regulators shared a common understanding that if NNSA were not provided resources matching China's industrial buildup, the probability of a severe nuclear accident happening at a Chinese nuclear power plant would increase.

Expressed most generally, the biggest nuclear safety challenge on the horizon for a continuously expanding nuclear power program in China is to put in place a robust nuclear safety culture everywhere and at all levels, from drawing boards to reactor operations. That challenge is daunting. Flaws found and reported by NNSA, for example, in design, manufacturing, materials, and oversight during welding examinations in safety-significant (including pressure-boundary) equipment at a number of power reactors in 2015 illuminate the depth and likely extent of safety culture challenges in a nuclear power program that over two decades has added several new reactors per year. NNSA identified and documented causes for these failures: poor supervision, manufacturing defects, insufficient testing of equipment, poor quality assurance, inadequate analysis of inspection results, lack of process control, poor skills in personnel, failure to check installed equipment against design specifications, failure to distribute up-to-date design data to field personnel at the plant site, and lack of experience feedback.²⁹⁹

Since Fukushima, the Chinese government has upgraded NNSA's status in the bureaucracy and assured greater funding and staffing. IAEA peer reviewers returned to China in 2016 after six years and noted progress. China has adopted safety regulations from foreign countries that have supplied the technology basis for much of its nuclear power industry and, according to IAEA experts, China is meeting IAEA safety fundamentals.³⁰⁰ Notwithstanding evidence of systematic safety culture problems in specific areas illuminated by NNSA at nuclear power plant sites, China has so far never reported a nuclear event rated at level two or above on the IAEA's nuclear safety scale rated from zero to seven, suggesting that China—unlike many of the world's nuclear power-generating countries—has never experienced a truly safety-significant nuclear mishap.

In September 2013, the National People's Congress called for the promulgation of a national nuclear safety law. NNSA favored the measure to establish its legal regulatory authority over China's civilian nuclear power program.³⁰¹ In September 2017, the law went into effect.³⁰² Before that, foreign safety experts told the author that they have seen evidence that NNSA has successfully intervened in some cases to prevent licensing and halt actions by nuclear power plant owners on safety grounds. But only with effective legislation in place and enforced can China's nuclear regulatory regime escape vulnerability to top-down and arbitrary political and bureaucratic interference.

In 2010, IAEA reviewers urged China to pay greater attention to the need to enact policies and better regulate nuclear waste management and the fuel cycle; in 2016, they reiterated that advice. Foreign government sources report that China has made plans to make a significant investment to build up human resources for its future nuclear fuel cycle, including in training, safety, and regulation.

Especially during the first two decades of China's nuclear development, some foreign experts worried that China's inexperienced and understaffed regulatory agency would be overtaxed by China's piecemeal approach to nuclear power development based on "boutique" nuclear power plants relying on different foreign technologies. In part for this reason, China, beginning in the 2000s, aimed to eventually standardize its nuclear program around a single PWR design. It is anticipated that most nuclear plants China will build in the coming years—even decades—will be based on the very few technologies that China is deeply familiar with, including the Hualong-1 PWR model that the government has ordered CNNC and CGN to develop jointly and perhaps larger Chinese versions of the Westinghouse-designed AP1000 PWR. Should China go forward with an industrial-scale closed fuel cycle and fast reactors, NNSA will need expertise to license and regulate these installations and activities. Peer reviewers advised China to build up fuel cycle regulatory know-how hand in hand with its plans to set up future nuclear fuel cycle industry centers.

Significant capacity issues for quality assurance and regulation will also come to the fore, especially if China continues to expand the nuclear program well beyond the level of 100 GWe. Standardization will ease China's regulatory burden, but the more nuclear plants China builds based on a single design, the more it must defend against common-cause failures in systems and equipment that could lead to costly and safety-significant problems at multiple units. These issues have arisen in France's nuclear program, which features many power plants with a high level of standardization. Chinese safety experts are currently working on how to screen out common-cause failures and identify design vulnerabilities.³⁰³ NNSA reports from 2016 suggest that Chinese experts are focusing more on this issue because China's nuclear power program has begun to encounter common-cause problems.³⁰⁴

Another equipment problem that may be more difficult to address is counterfeit or substandard components. This issue was first raised with NNSA in the 2000s by foreign governments whose industries are partnering with Chinese nuclear firms and were concerned about corruption and lack of quality assurance. An average nuclear power plant contains about 3,000 nuclear-grade valves, 250 pumps, 44 miles of piping, 300 miles of electrical wiring, and 90,000 electrical components.³⁰⁵ Considering China's possibly weak quality assurance for many of these off-the-shelf and common industrial items, companies and regulators must root out the threat that substandard, improper, or even fraudulent equipment could cause or contribute to a safety-significant accident. In recent years, NNSA has detected counterfeit components

that had been installed in nuclear power stations.³⁰⁶ There is a real possibility that this issue may lead to an accident if not rigorously pursued, as a modern Chinese nuclear power plant contains equipment from about 5,000 different suppliers. In a country with a relatively weak track record of industrial safety, where there is official pressure to favor indigenous technology and inputs, and where the manufacturing industry relies on competitive advantage from low costs, assuring the safety of an expanding nuclear power program may be considerably more difficult than elsewhere.

Continued expansion of China's nuclear power program will challenge decisionmakers to establish metrics for nuclear safety capacity and effectiveness. If China builds several hundred nuclear reactors toward 2050 and beyond, regulators and political leaders may have to decide at what point the risk posed by a projected *n*th nuclear power plant would be too great to accept based on their assessment of the country's nuclear safety capacity.

EXPORTS AND INTERNATIONAL TRADE

Beginning in the mid-1950s, the United States launched a long-term program called Atoms for Peace, which included bilateral peaceful nuclear cooperation with dozens of countries and encouraged U.S. industry firms to sell nuclear goods to Washington's foreign partners. Atoms for Peace was part of a strategic U.S. government effort to contain communism and combat Soviet influence. More generally, it was intended to enlarge America's sphere of influence, extend U.S. power globally, and, according to one National Security Council memorandum, "strengthen American world leadership" by diplomatic and commercial means through the dissemination of nuclear technology.³⁰⁷

The benefits of this program for the United States were considerable. Atoms for Peace made good on its promise "to make potential recipients interested in U.S. technology."³⁰⁸ U.S. nuclear industry vendors exported reactors to over fifty countries and sold enough wares abroad during three decades that, today, about three-quarters of the world's 450 nuclear power reactors are based on technology that was originally invented and patented by U.S. companies and their partners. The collaborative and commercial ties that were formed between U.S. entities and foreign companies afforded the U.S. government a window into strategic decisions by allies and other governments benefiting from U.S. know-how, equipment, and nuclear material. Through these relationships, the United States led the world during the entire second half of the twentieth century in the establishment of multilateral arrangements for non-proliferation, nuclear trade, nuclear safety, and nuclear security. The United States profoundly influenced the formation of global norms in all these areas.

In coming decades, China may assume the mantle of global nuclear leadership in critical areas, including international nuclear trade. As China's nuclear development has quickened,

Beijing has aggressively forced foreign companies and governments to transfer their intellectual property for nuclear reactors, fuel production, and engineering services to China, in line with a rigorous national economic development policy based on import substitution and zero-sum replacement of foreign technology by Chinese know-how. During the 1990s and 2000s, U.S. and French officials and entities appeared to challenge claims that China owned intellectual property for nuclear reactors that CNNC exported to Pakistan, then China's sole foreign nuclear reactor client.³⁰⁹ Today, however, China, like France and Japan in the last century, has largely succeeded in wresting free of foreign claims limiting its freedom to export nuclear power reactors and Beijing is now offering Chinese-branded nuclear equipment, including turnkey nuclear power plants, to foreign clients. China's struggle to obtain foreign intellectual property has resulted in U.S. espionage charges against Chinese military and company personnel.³¹⁰

At the end of the 2010s, and perhaps for years to come, the key to China's emancipation is likely to be Hualong-1 (also known as HPR-1000), the PWR design that Beijing ordered CGN and CNNC to collaborate on and market abroad. The design is based on two Chinese PWR models that incorporated older foreign technology and newer Chinese engineering permutations. China now claims it owns "complete independent" intellectual property for this reactor.³¹¹ As part of a comprehensive bilateral agreement, China aims to build Hualong-1 in the UK during the 2020s. In the meantime, China could export the reactor elsewhere.³¹²

Aside from the highly visible UK nuclear power plant sale, China has also forged nuclear cooperation arrangements with Algeria, Argentina, Iran, Jordan, Kenya, Romania, Saudi Arabia, South Africa, and Turkey. The need to meet technical licensing requirements may hold back export of Chinese wares to countries with advanced nuclear programs. But Chinese vendors will have the advantage of access to cheap credit. Above all, China's ongoing nuclear buildup has allowed Chinese vendors to set up a solid supply chain and develop expertise that can be quickly mobilized for new projects. By contrast, U.S. and European firms during the last two decades have lost expertise; their projects to build nuclear power plants outside of China have been set back by massive delays and cost overruns. China is building nuclear power plants at an overnight cost of about \$3,500 per installed KWe, compared to about \$5,500 for Europe. Analysts anticipate that Chinese industry will preserve its competitive advantage over Western competitors for decades to come.³¹³ In the meantime, the leading two nuclear industry companies in the West—Westinghouse and Areva—are mired in crisis-level financial difficulties due to lack of business outside China, loss of capacity, and mounting nuclear project risk following from deregulation of financial and electricity sectors.

In the coming years, Chinese firms that have invested billions of dollars in nuclear power plant manufacturing capacity will be tested by the "new normal" conditions. If the rate of new nuclear construction in China during the 2020s and 2030s is less than anticipated a decade

ago, China's nuclear export drive will be counted on to contribute to Xi's plan for Chinese industry to sell more high-value capital goods. This includes participation in the Belt and Road Initiative to spread China's political influence on the back of strategic exports—power systems, transportation lines, and port infrastructure—to destinations in southeast Europe, Southeast and Central Asia, and the broader Middle East.³¹⁴

Exporting PWRs would also provide relief to Chinese companies should they eventually invest in more expensive domestic infrastructure for advanced reactors and a closed fuel cycle. China might then also try to establish itself as the fulcrum of a regional nuclear fuel cycle scheme, in which China would build PWRs abroad, lease uranium fuel for those reactors, take back the spent fuel, and reprocess it to obtain fuel for domestic reactors. If such a system were able to function without serious legal and logistical bottlenecks, technical difficulties, or political impediments, it would increase China's influence among participating countries as the guarantor and custodian of nuclear fuel supply—especially if China agrees to retain nuclear waste from reprocessed spent fuel. As early as 2006, Chinese officials had considered the possibility of such an arrangement for neighboring states that were preparing to introduce nuclear power in the future. In the absence, so far, of firm plans by any more states on China's periphery to build nuclear power plants—as well as rising concern by China's neighbors about their freedom of action vis-à-vis Beijing—prospects for any such scheme during the 2010s have receded. Should a rationale emerge in coming years, the way forward will be difficult: discussions involving China and Taiwan and between China and German industry during the 1980s and 1990s, concerning the possible storage or disposal of foreign nuclear waste or spent fuel on Chinese territory, proved intractable partly because China concluded that it had greater leverage.³¹⁵

Historically, very few countries that have deployed nuclear power technology have become successful nuclear power plant exporters. The challenges China must overcome are considerable, including oversight, quality control, correction of mistakes, safety culture leadership, uniformity with international standards, and counterfeit equipment. If the schedule for a foreign nuclear project proves untenable, the pressure on Chinese contractors to cut corners may be great.

PUBLIC ACCEPTANCE AND POLITICAL RISK

China's nuclear energy program is firmly under the control of the central government and the ruling Communist Party. They command its funding, organization, oversight, management, senior personnel appointments, technology development and selection, investment, and all interactions with the outside world. To a greater degree than in other advanced nuclear power programs, China's rulers have very powerful levers to make and implement policy. Nuclear decisionmaking follows from a complex process of interactions, formal and informal, involving

officially acknowledged stakeholders in the executive government, China's administration and planning bureaucracy, SOEs, Communist Party organizations and leaders, official academic and science organizations, and the military. For nearly all of China's nuclear history, the people, writ large, have neither had much to say nor have they been asked.

When China launched nuclear power construction in the 1980s and 1990s, Beijing brushed off objections raised in signature petitions and arrested protestors.³¹⁶ Since then, China has not disclosed any safety-significant nuclear events or accidents and, for many years throughout its nuclear power buildup, China witnessed no public nuclear turmoil. As China's air quality deteriorated, the government has argued that expanding nuclear power production will reduce pollution. Especially in wealthy and information-dense east coast urban areas, where nearby nuclear power plants are substituting for base load coal-fired units, it would appear that China's urban population generally shares that view but also favors limiting the expansion of local nuclear capacity.³¹⁷

The accident at Fukushima and continued effects of globalization in China are changing this relatively static picture. In the wake of the accident, the Chinese population appears to be developing a more differentiated perspective about nuclear power and is more willing to intervene in the siting of nuclear installations. Immediately after Fukushima, Chinese authorities had to dispel radiation fears that led to a panicked rush to buy iodized salt in Chinese cities.³¹⁸ In 2013, protests erupted in the southeastern city of Jiangmen following the city government's announcement that a nuclear fuel processing complex would be built there. The installation would have been completed by 2020 and large enough to provide half the enriched uranium fuel required by China's nuclear power plants. China's nuclear SOEs will likely build the plant elsewhere. In August 2016, demonstrators objected, in what Chinese media described as violent clashes between protesters and police, to an announcement by the city of Lianyungang, in Jiangsu Province, that it had been selected as the site of the projected Areva reprocessing plant.³¹⁹

In both these cases, protests followed closed-door negotiations held by provincial and local city rulers with the central government and industry over terms for project approval, according to Chinese and Western government officials. Protesters objected that authorities had not given the public advance notice of these projects and little or no opportunity to comment or contribute to decisionmaking. Some protesters, in both cases, referenced the need for information and concern about radiation and environmental dangers in the aftermath of Fukushima.

While Chinese public opinion about the risks of nuclear power may, on balance, remain stable, public acceptance will be critical to the future of China's nuclear program in at least two areas. First, continued expansion of nuclear power in China directly depends on building plants at a number of proposed inland locations. Construction on any of these sites, which

was called for in the government's plans for accelerating nuclear development beginning in 2006, has been delayed until at least 2020 due to objections raised on safety and environmental grounds. In the meantime, China is permitting some "pre-authorization" work to take place at designated inland locations, apparently counting on the benefits from employment and investment to sway local communities to favor yet-outstanding political approvals that will be sought under the Fourteenth Five-Year Plan. Second, if China's population differentiates between nuclear power plant investments that bring valuable electricity and welfare to local communities as distinct from nuclear material processing plants that are concerned with radioactive waste and perceived to be risky, that could threaten Chinese ambitions for a closed nuclear fuel cycle. China's rulers are generally aware of this potential challenge: one year after the accident in Japan, NDRC introduced a mechanism for assessing the social and political risk associated with future large infrastructure projects into its planning process.³²⁰

Unlike in Western countries, opposition to nuclear power in China may be concentrated in rural areas rather than relatively wealthy cities dense with information and infrastructure. Fear of radiation may be widespread in rural China, and local communities are suspicious that the state will invoke rights of eminent domain to their disadvantage. Urban Chinese, by contrast, are counting on nuclear power to clean their air. Should China's power grid be outfitted with ultra-high-voltage lines permitting nuclear power to be generated in remote places and transmitted to megacities, local populations may object that they are assuming all of the risk for nuclear installations that benefit wealthy city dwellers. This factors into opposition to nuclear power plants in Japan.³²¹ In the debate over whether China should build nuclear power reactors at inland sites, coastal residents have complained that adding reactors at existing sites is no alternative "because we already have too much nuclear power."³²²

According to a government survey reported on by the Chinese Academy of Engineering in August 2017, "only 40% of the public supports the development of nuclear power in China."³²³ If true, China's success in overcoming public suspicion or opposition to nuclear power development will require the central government to be politically sensitive and proactive. In discussions about public acceptance in China, which the author participated in during 2014 and 2015, some Chinese experts dismissed nuanced concern raised by foreign industry executives and regulators that inland sites present a different risk profile than coastal sites. They also blamed anti-China politics in Hong Kong for opposition in southeastern China to nuclear construction in 2013.³²⁴ During the 2015 Carnegie workshop, Chinese experts explained that Chinese authorities were aware of technical challenges in demonstrating the safety of semi-arid inland sites with weak infrastructure for PWRs, and they added that Chinese industry and regulators would more generally be challenged to explain the concept of residual risk to a public that has very little knowledge about nuclear issues and that "expects a yes or no answer."³²⁵

STRATEGIC TAKEAWAYS

Moving ahead with its nuclear program, China will have to consider a number of challenges apart from questions of technology choice and economics.

- **Energy Security:** Driven by the expectation that it would generate nuclear electricity for hundreds of years, China has long assumed that it must close its nuclear fuel cycle to ensure that it does not run out of fuel. Because the timelines for uranium depletion have receded, China must assess the extent to which and for how long it will trust global market forces to provide uranium.
- **Nuclear Weapons, Nonproliferation and Nuclear Security:** Over the last twenty years, China has joined the world's nonproliferation and nuclear security regimes. Deploying more advanced technologies will increase China's responsibilities and raise its profile in this area. For Beijing to take on a global leadership role, it must go further than its current commitments, which are perceived outside China as minimalist and transactional. As a nuclear weapons state, future investment in technologies related to a closed fuel cycle may be assumed to also benefit China's nuclear defense.
- **Science and Technology Policy:** Especially given trends in China that favor industry protectionism, corporatization, and risk minimization, it remains to be seen whether or not Beijing will become a world leader in the transition to advanced nuclear technologies.
- **Nuclear Safety:** China faces numerous challenges from its historically weak industrial safety culture and the strain on regulatory capacity that has been exacerbated by nuclear growth. Barring measures to effectively generalize safety culture, more nuclear power reactors in China means greater risk.
- **Nuclear Exports:** After decades of aggressive intellectual property and import-substitution policies, China is poised to become a significant supplier of nuclear equipment and services worldwide. Success is not assured, but it would facilitate China assuming a leading role in global nuclear rulemaking.
- **Public Acceptance and Political Risk:** The Fukushima accident may have profound long-term impacts including: empowering regulators; encouraging aversion to risk; and creating political tensions between China's leadership and public over information transparency, equity, and center-periphery decisionmaking authority.

CONCLUSIONS AND OUTLOOK

Predicting China's future is a fool's errand. Some contemporary authors claim that China will soon collapse, others that China will instead dominate the world.³²⁶ No such narratives have captured the imaginations of analysts looking at China's nuclear power system but, based on information available for this report, one could derive two very different speculative boundary scenarios to describe the future of China's nuclear energy program.

If China's nuclear program moves along the trajectory Chinese strategists and scientists set forth three decades ago, perhaps by 2050 China will be operating several hundred power reactors, implementing a transition from PWRs to more advanced nuclear systems, and it may have demonstrated a closed fuel cycle at industrial scale. The government might reach an opaque compromise with stakeholders allowing higher costs for advanced technologies to be shouldered by Chinese taxpayers and ratepayers. China may be the world's leading nuclear exporter thanks to global rulemaking leadership and it may have invested enough in oversight infrastructure to manage its nuclear activities without suffering a severe nuclear safety, security, or proliferation accident. Forced development of nuclear and renewables may have cleaned the air in China's megacities by 2030, and the country may continue to invest in nuclear technology confidently assuming that it will rely on nuclear power for hundreds of years.

Alternately, by 2050, China may instead be preparing to wind down an ageing fleet of about 100 PWRs, having failed to effectively manage costs and overcome the economic, technical, and political challenges of commercially exploiting more promising and complex nuclear technologies. China's nuclear power plants may be threatened with obsolescence as a result of breakthroughs in alternative power generation and storage technologies. Over time, the companies that pioneered China's first big wave of nuclear plant investment in the 2000s and 2010s might not continue to assume the debt that sustained nuclear investment requires, especially if Chinese demand for power approaches the near-zero growth levels that obtain in many Western countries. Human resources may increasingly migrate to other fields, contributing to low nuclear plant availability, nuclear safety problems, lack of public trust, increased regulation, and corporate and government risk aversion.

No one can say whether either of these two possible but perhaps unlikely outcomes will happen because there are formidable unknowns. For China to succeed according to the first scenario, it would have to overcome severe technical barriers and achieve significant scientific and engineering breakthroughs that cannot be predicted. It must, for three decades, effectively control the flow of funds to and from nuclear organizations and assure that costs are manageable, predictable, and comparatively favorable. It must develop sufficient public trust and confidence to permit leaders to make decisions consistent with desired strategic outcomes. If China fails, its nuclear energy program may not sustain itself through the second half of the century. The second scenario will likely not materialize if the state makes economic policy adjustments to protect its nuclear assets, if technological innovation does not slash China's need for base load electricity, and, perhaps ultimately, if electricity policy is informed by the stark conclusion that lifecycle carbon emissions per kilowatt-hour from the coal-fired plants that generate over half of China's power are 70 times greater than emissions from nuclear plants.

After the Cultural Revolution, China's new leaders had short-term and long-term objectives. In the short term, they wanted to modernize the country and drag it out of poverty; in the long term, they sought to make China a great power. Nuclear energy served China's short-term agenda by shifting investments from the military to the civilian economy, and by supplementing the dirty coal that was burned to make electricity in China's east coast population centers. For its long-term agenda, China's R&D establishment declared nuclear power development a national strategic priority—even if very few people at the time fully grasped what that implied.

Two decades later, in the mid-2000s, Beijing dramatically magnified China's rationales for nuclear power as both the economy and the demand for electricity continued to expand indefinitely. Technocrats accepted the logic of their foreign collaborators that a global nuclear power renaissance was on the horizon. They expected that China's development model, fueled

by capital goods investment, would continue growing the economy at about 10 percent per year. Based on results from the 1980s and 1990s, projections for future Chinese electricity demand seemed to justify endowing nuclear power with a trajectory extending half a century. Converts to nuclear power added ambitious strategic missions to rid China of atmospheric pollution, develop intellectual property to further exports, and provide an ever-greater supply of electricity.

Guided by these expectations, China has massively invested in human and material resources needed to replicate the PWR-based systems that foreign countries had developed. Thanks to these investments, China will likely become the world's leading producer of nuclear electricity sometime before 2030. Straight-lining from China's considerable accomplishments during the last three decades would suggest that the nuclear share of China's electricity supply will increase from 4.5 percent today toward 10 percent in the 2030s; that nuclear power will help reduce atmospheric particulate emissions to Western-country levels and demonstrate China's leadership in mitigating climate change; and that China may become an important global supplier—perhaps the most important supplier—of civilian nuclear goods, including modern power reactors built at comparatively low costs. The mammoth task of decarbonizing China's overwhelmingly coal-fired power sector and cleaning the air breathed by 1.4 billion people may alone ensure that China will generate nuclear power in ever-larger quantities for decades to come. There are reasonable prospects that China's nuclear power program may continue expanding toward the second half of the century and perhaps beyond, as the country amasses infrastructure, experience, and human capital.

DOMESTIC CONSTRAINTS AND RISK

Whether China succeeds will depend greatly on how it perceives and manages risk and how it responds to constraints that, until recently, were not significant factors in nuclear decision-making.

China is investing in several advanced nuclear power-generating and fuel cycle technologies, and it may see one or more of these technologies through to the brink of commercial-scale deployment. But many of China's future options will probably remain niche technologies, and there will be no strategic breakthrough unless the state and its enterprises make very large, continuous, and potentially risk-laden investments. As of late 2017, China had not yet invested money in advanced reactors or reprocessing plants to match previous commitments by Western Europe, Japan, and Russia. Decisions made by Beijing in 2016 and 2017 suggest that China may well subsidize these projects, which, if continued and expanded, could provoke conflicts with other bureaucratic interests and government policy goals, including in China's electricity sector.

In coming decades, decisionmaking in favor of nuclear power may be subject to different and greater constraints than in the past. If so, factors that may contribute to limiting China's continued development include:

- **Growth trends:** After years of growth at or near 10 percent per year, the annual increase in China's GDP may stabilize at a lower level in the future. Power-demand growth, which in the boom years averaged about 9 percent annually, may gradually sink to modest or low OECD-country levels.³²⁷ The drivers of China's welfare may, in coming years, shift from electricity-intensive capital goods production to services and consumer spending. The capital goods-based model allowed China's economy to catch up, but some economists warn that it is creating more debt than wealth. If the shift happens and is accompanied by changes in the load profile of China's power system, the effect upon nuclear capacity expansion may be profound. Since the Twelfth Five-Year Plan, Xi has embraced the argument that China needs to switch growth models, especially following a 2013 joint World Bank and State Council report that advocated "green development" for China and deeper integration with the international economic system.³²⁸
- **Demographics:** Future growth will depend on whether China's aging population without a safety net will invest and consume, and whether rising wages and factor costs reduce China's competitiveness. Still-greater urbanization may increase electricity demand. For four decades, a relatively small coterie of engineers and technocrats with little public accountability built up China's nuclear infrastructure. During this time, China's wealth increased thirtyfold, and a richer population may demand greater performance legitimacy from China's leaders.
- **State-owned enterprises:** There are over one hundred SOEs in China, concentrated in strategic industries including nuclear power. They have contributed to increasing China's debt level since the 1990s toward 300 percent of GDP. The debt-equity ratios of all nuclear SOEs are at or exceed ceilings set by their shareholder, the State-Owned Assets Supervision and Administration Commission (SASAC). Beijing, meanwhile, aims to encourage profitability by tighter consolidation.³²⁹ In other areas of the Chinese economy, that approach has led to weak oversight, internal conflicts, poor communications, and inefficient operations.³³⁰ China's decision to include nuclear power equipment on a list of ten strategic industries as part of a "Made in China 2025" initiative might limit innovation, encourage protectionism, and lead to trade conflicts with foreign governments aiming to protect their own strategic nuclear industries.³³¹ Some economists argue that China needs to allocate capital away from SOEs and, beyond that, cut back on the cheap credit that has allowed SOEs to invest in excess capacity, including for power generation.³³²
- **Bureaucratic policy conflicts:** The overall direction of Chinese nuclear power decisionmaking is top-down, but there is plenty of internal friction among government

agencies and corporations, which may increase as competition among more stakeholders for marginally scarcer revenue and resources intensifies.³³³ Corporatization in nuclear firms may lead to conflict with the government over future technology development and selection, spent fuel management, investment policy, and risk-taking. Contradictions abound inside China's government over the fundamental direction of electricity policy. Since Zhu Rongji's premiership from 1998 to 2003, China's leaders have simultaneously favored both market forces and authoritarian rulemaking in the electricity sector. While the nuclear industry will urge the government to maintain current levels of subsidy and support—and, in the case of advanced technology, provide still-greater assistance—planners taking their cues from Xi appear dedicated to creating a power market for China in which the price of electricity will become the basis for consumer decisions and, ultimately, for investment decisions.

- **Risk aversion:** China's nuclear industry association has told the government that it can build six nuclear reactors a year and achieve a nuclear capacity of 150 GWe by 2030 only if Beijing approves inland sites for nuclear construction. Since Fukushima, a long-awaited government decision to build reactors in China's hinterland has for now become a political redline. The larger Chinese public became engaged in a debate about nuclear power for the first time, and this unfolded in ways familiar to observers in Western states after severe accidents in the United States and the Soviet Union. Some Chinese officials and experts have urged the government to slow down nuclear development and draw lessons from severe industrial accidents where lack of oversight was at fault.³³⁴ Safety concerns about inland sites extend beyond the issue of PWR water management to include discussion of whether inland sites have the sufficient infrastructure, logistics, and safety culture to support nuclear power.³³⁵ While the nuclear industry presses Beijing to permit inland plant construction, others in the central government bureaucracy argue that Xi's efforts to further centralize and expand political control will ultimately render China more risk averse.

Risk management is at the heart of decisions about the nuclear program's future. Beginning a decade ago, inland sites were designated for up to three-quarters of the reactors China aimed to build. For China's nuclear program to continue to expand as its architects have projected, the government must resolve questions about what are the risks in expanding China's nuclear program at these sites. Questions about Xi's centralizing influence aside, without the government and state-owned industry assuming additional project risk, a transition to advanced nuclear technology and a closed fuel cycle will not happen in China.

Since taking power, Xi has been extending the reach of the state and the Communist Party into Chinese society and the economy, and he appears to be prepared to burden the government with greater responsibility and hence greater risk. Some government officials express

concern about the state assuming more liability in part because, if things go very seriously wrong, China's political stability may ultimately be at stake. Close observers report that aversion to risk in China's nuclear bureaucracy is currently the rule rather than the exception. They offer several possible partial explanations for this, including the emergence of an increasingly complex consensus-finding culture; the legacy of Mao's dreadful social experiments; bureaucrats' fear that, under Xi, their superiors will punish their initiatives by charging them with corruption; and worry that controversial projects might halt the steady rise of Chinese real estate prices.

Decisionmakers know that if a severe nuclear accident were to happen in China, the population would hold the Communist Party accountable. This may give the leadership pause when mulling whether to deploy technologies that are perceived to bear greater technological, economic, and political risk.

What do these factors imply for China's nuclear development in coming years?

China set up its nuclear plant-building sector on higher expectations for capacity additions than prevail today, so China's industrial infrastructure is well prepared to arrive at the mid-century mark with a nuclear capacity of over 150 GWe and perhaps considerably more. But the developments described above and the knock-on effects of Fukushima have cut mainstream expectations for China's nuclear power capacity in 2050 to half of what optimists predicted a decade ago. Unless China's leadership rigorously challenges the primacy of the country's coal industry and finds an effective balance between renewables and nuclear power, future growth in nuclear capacity may decline.

Lower GDP and power demand growth, direct electricity sales by power generators to bulk customers at discounted prices, and overinvestment in generating capacity are currently besetting the outlook for China's electric power sector.³³⁶ Curtailments, which during the 2010s set back renewables, are now threatening nuclear power generators, forcing a few nuclear power plants to operate at about 60 percent of the capacity level required for these investments to break even.³³⁷ Industry and government will struggle over rules for feed-in tariffs, dispatching, and load distribution. So far, government policies favoring nuclear power have facilitated investors reaping average profits of 7 percent per year. Xi has strengthened the hand of nuclear companies, but that may blunt needed reforms.³³⁸

Nuclear plant owners will lobby for protection against newer, highly efficient coal plants reaping profits as high as 15 percent annually. Local governments will threaten to dispatch cheap coal-fired power, thereby squeezing reactor owners to sell power below the nuclear feed-in tariff.³³⁹ While central planners have ordered dispatchers to prioritize putting nuclear power onto the grid, the State Council's political leadership appears to favor renewables instead.³⁴⁰

Nuclear investors, fearing a decline in feed-in tariffs, will warn Beijing that without continued or greater relief from the state, their plants may become stranded assets. To observers in the West, this looks like a familiar script, pitting the nuclear industry and its advocates who warn about high costs, dirty air, and climate change against market ideologists, a protected and influential renewables sector, and a powerful and entrenched fossil-fuel industry. Inside China, some nuclear executives and officials calculate that if the government goes further with electricity reform, saving China's nuclear power sector will require that the government guarantee that base load power will be nuclear-generated, provide direct financial subsidies for nuclear plant construction and operation, and enact a carbon tax.

If new normal conditions in China's economy and power sector prevail, investment in more advanced nuclear technologies may be discouraged and China's nuclear power investors and generators inclined to remain conservatively focused on maintaining their PWR-based infrastructure. If so, China's nuclear power system by mid-century might look like a larger version of current nuclear power programs in North America and Western Europe—including their problems. Continued corporatization of China's nuclear firms may incline executives to resist assuming greater project risk associated with nuclear technologies that have no proven commercial track record.

The biggest unknowns are how much electricity China will need in coming decades, and whether policymakers and industry will permit nuclear sources to meet an ever-larger share of that demand. Regardless of policymakers' and analysts' near-term focus on China's new normal, a senior Chinese nuclear power industry executive in November 2017 confidently projected that if China's power demand grows indefinitely at a rate of 5% per year, China's demand for electricity “will double in a couple of decades.”

STRATEGIC AMBITIONS

Should conservatism and aversion to risk increase and prevail among Chinese executives and nuclear technocrats, that would set up a conflict with nuclear planners in the Chinese state who, for three decades, have viewed nuclear energy as a strategic technology.

The contrast between current conventional Chinese and U.S. perspectives on the future of nuclear energy is stark. Many Americans believe that nuclear power is a transition technology toward something else—perhaps something that has not even been invented yet—within the century. Chinese experts have come to expect instead that nuclear power—from conventional reactors, breeders, and fusion plants—will be required for hundreds of years. They are conservatively inclined not to dismiss an available and reliable energy resource that in principle could replace a significant share of the coal currently generating about three-quarters of China's power, and that might also help spread China's influence worldwide.

The end of the 2010s marks a crossroads for China, as it works toward the likely achievement of producing more nuclear electricity than any other country and ascending to a leadership role in global nuclear technology. China will have to decide how much nuclear power it wants to produce in the future and with what technologies, how it will assess and manage the risks associated with continued nuclear development, and how it will manage its economy to accommodate its nuclear investments.

Since the 1980s and until now, China has followed, albeit very prudently, in the steps of advanced nuclear states that have long counted on moving beyond LWR technology and deploying fast neutron breeder reactors, under the assumption that open-ended population growth, economic development, and urbanization would require ever-greater amounts of electricity. Faced with the certainty that the supply of readily available conventional nuclear fuels will diminish, fast reactors could provide increasing amounts of nuclear fuel through the conversion of uranium to plutonium.

In theory, these reactors could produce a surfeit of plutonium fuel, permitting China to comfortably cover a large share of its electricity requirements by the end of this century. Today's PWRs are, in the view of some Chinese R&D experts, a spent force. Costs for PWR systems may increase as more safety-related redundancies are added, discouraging innovation and leading to their obsolescence. By 2200, China might instead meet its entire demand for nuclear energy using breeders, fine-tuning their plutonium production to meet China's anticipated energy demand for a very long time.³⁴¹

In reality, the obstacles that China must overcome to make this happen are exceedingly formidable. Unlike the PWRs that China has been replicating for a quarter century, the technology for advanced nuclear systems "cannot be introduced until it is demonstrated," Bernard Bigot, a leading French nuclear energy official, told an IAEA fast reactor conference in Paris in 2013.³⁴² A number of countries tried without success for over half a century to operate industrial-scale fast reactors at a sustained high capacity and low cost. If they keep trying, France's energy minister warned the same Paris audience, they will fail, unless they minimize the risk of accidents, achieve greater public acceptance, and make technology and design improvements.

China is now poised to begin construction on an industrial-scale fast breeder in tandem with a reprocessing plant to provide enough plutonium fuel to perhaps operate the reactor at equilibrium sometime in the 2030s. China's nuclear technology planners have urged that both installations be completed by the mid-2020s.

On the basis of China's limited experience and the past records of other countries, this timetable is ambitious. France built two breeders in succession and then operated them for over two decades before commissioning a bigger unit to demonstrate power generation. Japan

commissioned an industrial-scale fast reactor seventeen years after it started up a pilot reactor that eventually operated at twice the power level of China's experimental fast reactor. Both France and Japan established industrial reprocessing capabilities along these same timelines. Russia, with arguably the world's most successful fast reactor program, took thirty years to operate a 600-MWe industrial-scale reactor; before that, Soviet engineers successively built and operated a half-dozen critical facilities and reactors, including a 300-MWe prototype.

While serial deployments of off-the-shelf PWR technology have proceeded smoothly, China has experienced recent delays in setting up more advanced PWRs. Decisionmakers may conclude that more time is needed to complete complex and unique fuel cycle projects. Some of the predictions and scenarios for fast reactor development set forth by Chinese R&D officials in recent years are, by all accounts, unattainable.

It should not, however, be assumed that China will fail because other fast reactor programs have not established themselves at the industrial scale. Ultimately, China might master the technical challenges required to begin operating an industrial-scale fast neutron reactor sometime before 2030, build and operate a reprocessing plant needed to produce tons of plutonium needed for start-up of the reactor, and also learn how to make the fuel. If China succeeds, it will match and may well exceed the limited progress made by other countries during the second half of the twentieth century toward closing the nuclear fuel cycle. If, in addition, China is able to develop metallic plutonium fuel and achieve breakthroughs needed for industrial-scale pyroprocessing of spent fast reactor fuel—and, beyond that, demonstrates that fast reactors can be operated economically to generate large amounts of electricity and, in the process, produces and effectively and securely uses large amounts of plutonium as fast reactor fuel—it will make strides that have eluded all others so far. But the technical and economic hurdles, including for the development of industrial-scale systems, are severe, and the timelines may be considerably longer than some Chinese planners claim.

A CLOSED FUEL CYCLE FOR CHINA?

Xi had been in power for two years when Zhang Donghui, a director at CIAE, told IAEA experts in 2013 that China's deployment of fast reactors would depend on specific conditions. One was that the cost should be lower than for a coal-burning plant—a tall order even assuming current government assistance to nuclear investors and plant owners. Echoing counterparts in Japan and South Korea, Chinese nuclear executives refrained that if China builds reprocessing plants and breeders, the government must pay for extra construction and power-generation expenses. This might imply that instead of reducing nuclear power generators' off-take price, Beijing should increase price supports—maybe over the heads of Xi's central planners and researchers who want to eliminate market-distorting exceptions.³⁴³

Long before the new normal appeared on the horizon, China's decisionmakers behaved with great prudence in moving forward on nuclear fuel cycle plans. Until the late 2010s, China was not prepared to undertake considerably more nuclear-power-program risk for the fuel cycle than it has incrementally and modestly assumed by deploying conventional nuclear technology for the last three decades.

Decisionmakers are aware that China's nuclear power system would likely fail to transition to fast reactors using plutonium fuel if one or more of the following happen:

- Fast reactors experience recurring technical problems, leading to a loss of availability, higher costs, or political or public acceptance issues.
- The industrial-scale reprocessing and/or pyroprocessing of spent fast reactor fuel and fast reactor fuel fabrication proves technically and logistically difficult, time-consuming, and prohibitively expensive.
- Technology breakthroughs in other areas appear to comparatively disadvantage advanced nuclear systems and are favored by decisionmakers.

Particularly if fast reactor technology advocates force the pace of future indigenous development and deployments, China's fast reactor program might encounter problems similar to those that set back foreign programs during the 1980s and 1990s. So far, the CEFR has reportedly not experienced any serious sodium leaks or fires, possibly because China incorporated improvements, including those made by Russia at the BN-600 unit. In larger reactors designed for power generation, challenges will be greater. Indeed, Russian officials queried for this report warned Chinese counterparts not to underestimate the challenges of plutonium management in a fast reactor program. Russia, for decades, used uranium instead of plutonium in its breeder program because project management absorbed early painful lessons from plutonium fuel shortages and fuel fabrication issues. If China needs several tons of plutonium for equilibrium operation of a single big fast reactor, one expert said, "it will be a long time before China has enough separated plutonium and fuel fabrication capacity."

Because reprocessing and the fast reactor were developed for industrial application beginning half a century ago, the engineering challenges associated with these technologies are generally well understood. Experience deficiencies are most apparent concerning reprocessing of spent fast reactor fuel (more generally, for spent fuel with high burnups and high plutonium content) and concerning the future development of pyroprocessing technologies that China and some other countries aim to use in future fast reactor fuel cycles. In the meantime, Beijing may have to decide whether and for how long to use MOX fuel in its fast reactors, especially given China's relative inexperience and its long-term interest in metallic fuel and pyroprocessing.

Decisionmakers in Beijing are doubtless aware of the drawbacks should China prematurely commit itself to obsolescent technical solutions to engineering problems, including for generating electricity. Apart from fast reactors, China is presently investing in other nuclear and energy technologies. Potentially game-changing nuclear and non-nuclear innovations, including for battery storage of electricity, have very long lead times into the 2030s and beyond. Should any of these achieve a significant breakthrough, investors may favor it instead, especially if the development of fast reactors and reprocessing-related technologies is delayed. Should China's power system focus increasingly on distributed generation, electricity planners may shift their nuclear technology interest away from big reactors and toward SMRs.

China has put forth two important rationales for deploying fast reactors and reprocessing plants in this century. The first is energy security, based on the assumption that the supply of uranium will, in the coming decades, become depleted. The second rationale is that these technologies will provide clear net benefits for waste management. As China approaches 2020, it has not yet been established beyond a doubt that either of these rationales is valid.

Zhang told the Paris IAEA group that, for fast reactors to be deployed, uranium would have to be "expensive enough."³⁴⁴ Other Chinese experts, including at Carnegie workshops, share this view.³⁴⁵ Independent of Chinese perspectives that nuclear power will be needed for centuries, most analysts believe that, for several decades at least, market fundamentals should not cause uranium prices to dramatically rise, and that rising prices thereafter would likely coax out increased supply; if so, fuel security concerns alone should not prompt China to rush into fast reactor and reprocessing plant deployment.

In favoring reprocessing and fast neutron reactors, the government has followed the argument that the reduction of radiotoxicity in spent fuel would be a significant benefit, since unprocessed spent fuel would require over 100,000 years to achieve the same radiotoxicity level as natural uranium. A more benign long-term perspective is that after 500 years, most of the radioactive elements in unprocessed spent fuel will have decayed. The remaining radiotoxicity is mostly determined by isotopes of plutonium and americium that, if buried underground, should exhibit very low solubility and mobility. After 1,000 years, radiotoxicity will be only 1.5 percent of the initial discharge level of the spent fuel, and the heat emitted by the spent fuel will be equivalent to that emitted by an adult human.³⁴⁶

During two IAEA peer reviews of China's nuclear regulatory safety oversight system in 2010 and 2016, reviewers urged China to focus more attention on nuclear waste, spent fuel, and fuel cycle management. The IAEA's judgment was consistent with a 2015 verdict from CAS that China was far behind other countries in the fuel cycle and that knowledge was scattered piecemeal throughout Chinese institutions.

Government policy has favored the closed nuclear fuel cycle since the 1980s, and Beijing has spelled that out to all nuclear R&D institutes and industry firms working on possible future nuclear energy systems. “They tell us that if our reactor concept doesn’t include spent fuel reprocessing, it has no chance of being accepted,” one R&D official said in 2017. So it is no surprise that the draft of a national atomic energy law, which Xi wants to push through as soon as possible, makes it clear that China’s spent fuel should be reprocessed as a matter of policy. During discussions on the text of the law, it was proposed that reprocessing should be conditioned upon practical needs as well as the maturity and economics of available technology. If that principle is accepted, then China’s law might not ordain expeditious reprocessing of reactor owner’s spent fuel but permit them to “wait and see” until there is agreement among stakeholders that the terms of the law governing reprocessing are fulfilled.

MARKET FORCES AND OTHER UNCERTAINTIES

Two multilateral collaborations on development of advanced nuclear power systems, GIF and INPRO, were set up after a number of leading nuclear energy countries singlehandedly tried unsuccessfully to commercially establish the plutonium fast reactor. Veterans of Japanese and European breeder programs during Carnegie workshops discouraged China from trying to accomplish a closed fuel cycle alone. According to one of these experts, when France halted its industrial scale breeder project in 1997, “Japan was thereafter by itself, and that contributed to our lack of success.”³⁴⁷

Chinese decisionmakers will therefore observe carefully how France and Russia, which presently lead in advanced fuel cycle industrial development, proceed in coming years. A forthcoming decision by French industry whether to commit to an expensive refurbishment of Areva’s La Hague reprocessing complex might be a signpost. Likewise, if Russia moves forward successfully with planned milestones for its fast reactor program—100 percent MOX loading in BN-800 in 2019, reprocessing at a new plant at Krasnoyarsk, and industrial-scale closed fuel cycle demonstration in 2029—China may be encouraged to continue on its charted course.

In every country that has established a nuclear power program, the role of the state was critical and essential. For three decades, China was no exception. Shortly after Wen Jiabao decided in 2005 to accelerate nuclear power investment, Beijing reacted to an international financial crisis by granting China’s nuclear power sector an assistance package worth half a billion U.S. dollars. The current leadership professes to be more market-oriented. In 2013, at the third plenum of China’s Eighteenth Party Congress, Xi brought forth a so-called Sixty Points reform agenda. It called for “letting the market play the decisive role in allocating resources.” Firms would compete for access to capital “while the government would retreat to the responsibilities of macroeconomic manager and market regulator.”³⁴⁸ That might mean that China

will proceed with reforms that could destabilize its nuclear power program.

But it might not—the Sixty Points plan also says that policy implementers must “persist in the dominant position of public ownership, give full play to the leading role of the state-owned sector, and continuously increase its vitality, controlling force, and influence.” It should therefore not be expected that China will transform economic decisionmaking strictly according to market-model blueprints. China may elect to resolve conflicts somewhere in between the desire for market mechanisms in its electricity supply system and the desire to protect nuclear assets by making exceptions to future rules. In urging Beijing to continue to provide nuclear firms state assistance, some Chinese nuclear industry officials argue that China’s subsidized nuclear feed-in tariff should be considered as a form of carbon taxation. Until now, China’s strategic calculus about the nuclear fuel cycle has not been fundamentally driven by economics, and Beijing may be willing to pay for initial demonstration projects—as other governments in the past have done—and perhaps also for large-scale future nuclear fuel cycle industry centers.

Especially if Chinese nuclear R&D advocates get their way, market pressures could paradoxically result in a decision to accelerate deployment of reprocessing plants and fast reactors—even if uranium is cheap and fast reactors are expensive—because the future political decisionmaking environment in China will be expected to become increasingly adverse toward these investments. One senior Chinese R&D scientist in 2016 said, “We need to close the fuel cycle now because as time goes by, it will become more and more difficult to do it, and in a few years the window will close.”³⁴⁹ The prospect that the forces of globalization and corporatization might eventually prevent China from realizing its closed fuel cycle vision was echoed in 2014 by a high-level U.S. government official who had been discussing bilateral cooperation with Chinese counterparts: “The more meetings we have, the more it seems that their nuclear program in a few years could look like ours”—firmly focused on PWRs and with little appetite inside corporate boardrooms and government agencies for assuming additional technological or project risk.

Industry experts from Russia, Western Europe, Japan, and the United States attending Carnegie workshops concurred that the cost of setting up facilities for a closed industrial nuclear fuel cycle will be daunting and, said one, “that cannot be left to the market.” In Western countries and Japan today, these experts said, it would be unthinkable that a nuclear power plant owner-operator would on its own make an investment in a fast reactor and associated fuel cycle installations for the purpose of generating electricity. In China’s far more strategic calculus, economics may not be a show-stopper, but stranded investments must be a concern and decisionmakers may seek a solution that permits China in the short term to continue to advance and protect its nuclear fuel cycle know-how while avoiding making hasty commitments to technologies that may become obsolescent. “Without a clear road map [for] future

fast reactor technology, a reprocessing plant based on PUREX could prove to be a wasted investment depending on what else comes along.”³⁵⁰

For China, the ultimate consequence of hedging on its future nuclear fuel cycle investments would be to accept the possibility that its fundamental assumption—that China will need nuclear power for hundreds of years—may be wrong. As one French government nuclear official familiar with China’s nuclear fuel cycle program put it in September 2017: “If in a decade or two there is a revolution in electricity storage technology, then by 2050 all our power will come from renewables and batteries.” Should such logic prevail in light of great uncertainty about future technology development, China’s forthcoming decisions now through the 2020s about a closed nuclear fuel cycle might not be yes or a no. Instead, and despite the risks that some know-how and industrial capacity might be lost, China might elect to pursue a deeper and more extended R&D program, including on fast reactor development and reprocessing technology, that extends beyond 2030. “If China spends its money doing 15–20 years of nuclear fuel cycle R&D, it will learn more things.”³⁵¹ In two decades, the prospects for fusion energy, advanced fission energy fuel technologies, key non-nuclear technologies, and, more generally, the global risk profile and economic environment for nuclear power, may be more confidently assessed than today.

STRATEGIC IMPLICATIONS BEYOND CHINA

Decisions that China makes about the future of its nuclear power program will have repercussions beyond its borders, affecting other countries’ energy, foreign, industrial, and technology policies; and perhaps even their strategic alliances.

THE FUTURE OF NUCLEAR POWER AND THE NUCLEAR FUEL CYCLE

For at least a decade to come, China will be the focus of a large portion of the world’s nuclear power investment. If new normal conditions prevail, and if deployment of new nuclear power plants does not follow from a policy aiming to aggressively reduce coal-firing, China might join states in North America, Europe, and the rest of the Asia-Pacific in reaching a saturation point in nuclear power investment in a decade or two—but at a record level.

Beginning mid-century, China will face decisions about technology selection to replace aging PWR-based nuclear power plants. China’s choice will depend upon whether it succeeds during the next thirty years in introducing alternative power generating technologies, and also upon the architecture of China’s electricity system, including whether China will indefinitely require a significant amount of base load power. If China succeeds in demonstrating advanced nuclear technology, including in the fuel cycle, that achievement might dramatically revise global expectations upward for the future of nuclear power. Other states may then accelerate nuclear investments including in modest or idled R&D programs.

If China does not succeed, lack of progress may translate into lost commitment by government, and especially industry, as has been the case in other countries. Chinese failure would reinforce the widely held assessment that fast reactors fueled with plutonium will prove too expensive. Independent of the results from ongoing activities in other countries actively pursuing the closed nuclear fuel cycle—France, India, and Russia—lack of success by China will reduce the prospect that industrial fast reactor programs in other countries would be politically sustainable.

Should China suffer a severe nuclear accident, the political fallout and adverse effects on the world's confidence in nuclear power would be considerable. If the Chinese leadership adopts a very long-term perspective, it is possible that a severe accident would prompt the conclusion that a nuclear power program with over a hundred reactors is too big to fail. Over time it is likely that the state will continually assess its risk as it continues to deploy nuclear technology. "The more reactors we have," one Chinese planning expert told the author, "the greater our liability. At a certain level it's a simple addition of probabilities."

NUCLEAR EXPORTS AND STRATEGIC LEVERAGE

With a determination not anticipated until recently, China is now stepping forth as an ambitious nuclear power plant vendor state. Beijing is consolidating SOEs to create a national champion nuclear export product. Established nuclear industries in France, Japan, South Korea, and the United States will be challenged by Chinese firms that can provide its clients favorable financing, low prices, and an experienced supply chain. Especially if China makes progress in advanced fuel cycle technology, its industry will be positioned to offer nuclear fuel, as well as services for uranium conversion and enrichment, logistics, engineering, commissioning, operations, construction, and spent fuel and waste management. For at least two decades, Chinese companies may enjoy lower factor costs than Western firms, which are losing their know-how and face greater restrictions on financing and requirements for transparency.

Chinese vendors, however, must surmount certain risks in the 2020s and perhaps beyond. If their debt levels remain acute, their risk-taking will be limited and government support could be constrained. Some Chinese planners and managers are anticipating a slowdown in the rate of nuclear capacity additions in China. Their plan is to compensate for this by exporting. Should a substantial increase in the global demand for new nuclear power plants fail to materialize, China's nuclear power plant builders, like their foreign competitors, will be threatened with idle capacity and loss of knowledge. China will not benefit if it drives foreign firms out of business; as competition dwindles, Chinese firms may become less transparent, less innovative, and less well managed. Potential clients will decide against nuclear power if they conclude that there is no alternative to Chinese vendors, and threatened foreign firms and their governments may raise grievances at the World Trade Organization or other venues.

Should China, perhaps alongside Russia, lead the world in supplying nuclear materials, technology, and equipment, it may duplicate the success of the U.S. Atoms for Peace program to extend its influence into the foreign, energy, and technology policymaking processes of its clients. As its nuclear power program acquires more depth and experience, China may offer training, research reactors, and regulatory and non-power technical assistance, in addition to power plants. Robust nuclear power diplomacy and commercial activity would serve Beijing's aim of extending Chinese influence in the world. With this in mind China has included nuclear technology in its Belt and Road Initiative and aims to enlarge the sphere of its nuclear cooperation in South America, Africa, and the Middle East—all regions that Beijing has identified as strategically important. In advance, China's leading nuclear SOEs have for now divided up the world market into future spheres of influence on a country-by-country basis.

INTERNATIONAL NUCLEAR GOVERNANCE

The bigger and more technologically advanced China's nuclear program becomes, and the more wares China exports, the greater China's voice will be in multilateral nuclear rulemaking organizations and arrangements. These include the IAEA, the NPT, the international conventions on nuclear safety, nuclear security, and nuclear assistance, the GIF, and the NSG. Should China succeed in establishing a closed nuclear fuel cycle, it may seek to make changes in global governance concerning the management of nuclear materials and nuclear waste that would have impacts on security, nonproliferation, transparency, and safety. China may also use its nuclear diplomatic power to establish Chinese standards and codes for nuclear equipment, construction, and management, and it may challenge norms that have been established by industries and governments in the United States and other countries. China may be less inclined than Western countries to condition nuclear commerce with client states upon bilateral obligations that exceed least common denominators in multilateral arrangements and it might adopt a more opportunistic approach to nuclear governance in the nuclear trade regime.

Beyond a narrow group of states with advanced nuclear programs that already have experience with fast neutron reactors and plutonium fuels, it is not apparent that other states would embark on reprocessing programs should China commence with reprocessing of its power reactor spent fuel. It is possible that if China demonstrates that advanced nuclear fuel cycle technologies are sustainable at the industrial scale, raising their profile, more states would pursue sensitive nuclear activities. Other nuclear weapons states would likely lead the way, but some countries might be inclined to launch nuclear fuel cycle-related activities as a hedging maneuver. An international rule-making effort including China would be needed to ensure that nuclear materials generated in closed fuel cycles would be managed without magnifying proliferation and nuclear security risks. Given that industrial-scale fast reactors and reprocessing plants have been operated in some countries without leading to horizontal proliferation,

achieving this goal in China and other countries may be possible but that would depend on how policymakers assess proliferation and security risks against the benefits of energy production and technology development.

The world's nuclear supplier states are currently committed to transferring sensitive fuel cycle know-how with great restraint. Should China succeed in closing the nuclear fuel cycle, advanced nuclear states will need to strengthen that commitment and develop global collective understandings to limit and govern the deployment of fast neutron reactors and reprocessing plants worldwide. This should be supported by multilateral programs that currently facilitate development of advanced nuclear power and nuclear fuel cycle systems. Should nuclear power generation worldwide also expand, a China that inspires confidence in its respect for the rule of law might serve as the future hub of a multilateral nuclear fuel cycle arrangement, which may include reprocessing of spent fuel and recycling of the recovered nuclear materials in Chinese power reactors and China leasing fresh fuel to client states operating PWRs. China and other advanced nuclear states might agree to restrain transfer of fast reactor and reprocessing technology to others, but the longstanding U.S. view that the civil "plutonium economy" represents a net global hazard would come under pressure, including in bilateral and multilateral nuclear diplomacy.

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