AVC-VTN-21N01

China's Civil Nuclear Sector: Plowshares to Swords?

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Topical Technical Report
Under DOS Contract No. 19AQMM19P2400
(10/1/2020- 3/31/2021)

Submitted to
U. S. Department of State
2201 C Street, NW
Washington, DC 20520

April 2021

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
31 March 2021

2. REPORT TYPE
Topical Report

3. DATES COVERED *(From - To)*
1 Oct 2020 - 31 March 2021

4. TITLE AND SUBTITLE
China's Civil Nuclear Sector: Plowshares to Swords?

5a. CONTRACT NUMBER
DOS 19AQMM19P2400

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Henry D. Sokoloski (Ed.)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Nonproliferation Policy Education Center, 1600 Wilson Blvd., Suite 640, Arlington, VA 22209

8. PERFORMING ORGANIZATION REPORT NUMBER
NPEC Report No.2102

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of State / Bureau of Arms Control, Verification, & Compliance
2201 C Street, NW
Washington, DC 20520

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AVC-VTN-21-N01

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified//Public Release Authorized

13. SUPPLEMENTARY NOTES
Jointly funded with the MacArthur Foundation, the Scaife Foundation, and the Carnegie Corporation of New York.

14. ABSTRACT

The Defense Department determined last fall that China had a nuclear arsenal in the "low 200s," and that it could "at least double" it by 2030. Subsequently, the US claimed China could triple or quadruple its current arsenal by 2030. These estimates, however, failed to factor in China's planned "civil" nuclear program or China's plutonium fast breeder reactor program, which will be capable of producing a significant amount of weapons-grade plutonium. If one includes it and China's nonweaponized military stockpile of weapons-grade plutonium, China conservatively could obtain roughly 1,270 warheads by 2030 — nearly as many as America currently has deployed on its intercontinental-range ballistic missile force. China has a variety of additional nuclear materials production options that could increase this number by a factor of two or more. Production of weapons-grade plutonium from its fast reactor program, however, is the least burdensome approach to enlarge its arsenal of advanced, two-stage thermonuclear weapons. What is troubling is China agreed to report annually to the IAEA on what China's civil plutonium holdings and production capabilities are but stopped doing so in 2017. The United States, which also files these reports, should ask China why. Before China completes construction of its fast reactors and plutonium reprocessing plants, Washington should also explore with Beijing, Tokyo, and Seoul pausing commercializing fast reactor fuel cycles, all of which are exceedingly uneconomic in comparison to other forms of nuclear and nonnuclear electricity production.

15. SUBJECT TERMS
China; Nuclear Weapons; Fast Reactors; Reprocessing; Civil Nuclear Energy; Enrichment; Projections of China's Nuclear Arsenal

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU	158	Rongsong Jih (COR)
					19b. TELEPHONE NUMBER *(Include area code)* +1-202-647-8126

OCCASIONAL PAPER 2102

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March 2021

NPEC
Nonproliferation Policy Education Center

Nonproliferation Policy Education Center
Arlington, VA 22209
www.npolicy.org

Printed in the United States of America

Cover images, from top left clockwise: 1) China's first experimental fast breeder reactor under con-truction in Tuoli, China in June 2004; 2) an enlarged satellite image of the demonstration reprocess-ing plant on March 12, 2020, in Jinta, Gansu Province; 3) the People's Republic of China showcasing new Dong Feng 41 (DF-41 / CSS-X-10) missiles at its 70th anniversary military parade; 4) operators of China National Nuclear Corporation's (CNNC) large-scale demonstration centrifuge project at the Hanzhun fuel facility in Shaanxi province.

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Nonproliferation Policy Education Center
Occasional Paper 2102

March 2021
Series Editor: Henry D. Sokolski

Nonproliferation Policy Education Center

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Contents

Acknowledgments

This volume of research was supported by grants from the MacArthur Foundation, the Scaife Foundation, the Carnegie Corporation of New York, and the US Department of State's Bureau of Arms Control Verification and Compliance. Brooke Buskirk is responsible for the volume's formatting and assembly. The research, of course, would not have been possible without the contributions of the volume's authors.

Preface

This is an important and worrying report.

It is widely known that the People's Republic of China (PRC) is expanding its arsenal of nuclear weapons, which at this point even its own diplomats do not much trouble themselves to deny. What is less clear, however, is how fast this build-up is occurring and – most critically – how long and to what level Beijing intends to continue this expansion.

This new *NPEC Occasional Paper* on "China's Civil Nuclear Sector: Plowshares to Swords?" does not answer those questions. It does, however, provide new insight into the degree to which China's current trajectory in the civil nuclear arena will have the result of placing enormous additional quantities of weapons-usable plutonium into the hands of the Chinese government as that country moves into large-scale plutonium reprocessing in order to produce fuel for a new generation of plutonium-fueled breeder reactors.

The two of us served consecutively as U.S. Assistant Secretary of State for International Security and Nonproliferation, and we both for a time additionally fulfilled the responsibilities of the Under Secretary of State for Arms Control and International Security. We have worked long and hard for presidents who could hardly be more different, we support opposing political parties, and we most assuredly disagree about many of the more important issues in American foreign and national security policy today.

Yet despite our very different perspectives, we agree – as foreign policy and national security professionals – that there is essentially nothing good that can be said about the prospect of the PRC acquiring an additional 1,440 additional kilograms of weapons-grade plutonium from the two "civilian" breeder reactors it is presently constructing – nor about the additional 110 kilograms of plutonium that China could recover by processing material from its small experimental fast breeder reactor.

This expanding Chinese reprocessing program is especially problematic, not to mention hypocritical, in light of China's own oft-expressed security concerns about the very large plutonium stocks still held by its neighbor Japan. After more than 40 years of pursuing the plutonium option for power generation, Japan is still far from making it economically competitive with other nuclear and non-nuclear options, and has accumulated many tons of plutonium, the disposal of which in non-breeder reactors would take decades to accomplish, even assuming its whole reactor fleet still returns online. China claims to see that stockpile as a potential threat, even though Japan would have to work quite hard (as well as break its treaty commitments) to convert such material into nuclear weapons, since, thankfully, it lacks both a nuclear weapons production infrastructure and systems for delivering any such weapons to their targets. China, however, lacks neither of those things, and is moreover presently engaged in a large nuclear weapons build-up that U.S. intelligence officials publicly estimate will result in *at least* a doubling (or more) of the size of Beijing's nuclear arsenal – which today is only a small fraction the size of the U.S. or Russian arsenals – over the course of the next decade.

To be sure, there is at present no evidence that China intends to divert its potential new plutonium horde to weapons use, though Beijing continues to be rather conspicuous in its refusal to adopt a moratorium on fissile material production for weapons purposes and has collaborated with Pakistan for many years to prevent the U.N. Conference on Disarmament from negotiating a Fissile Material Cutoff Treaty. Our concern and that of this study is not that Beijing necessarily *intends* to divert these huge quantities of plutonium to weapons, but that *it could* do so and might yet choose to – and that China's civil-nuclear excursion into the "plutonium economy," an effort that is neither technically necessary nor likely to be economically worthwhile, represents a colossal global security liability. As this report makes clear, if China opted to divert its burgeoning civil-nuclear plutonium program to weapons purposes, it could increase the size of its operational nuclear arsenal to a level approximating those of the United States or the Russian Federation.

China's determination to pursue plutonium reprocessing and breeder reactors seems to be driven by its desire to dominate the future's cutting-edge technologies, as part of the Chinese Communist Party's broader agenda of making the PRC the pre-eminent world power by 2049 – the centennial of the Party's seizure of power. Most technically capable countries, however, have correctly concluded that fueling fast reactors with plutonium is better described as "pipe dream" than "cutting-edge." As this report demonstrates, creating more plutonium (beyond the c.500 tons humans have created since the 1940s) will not solve the essential problem: plutonium is a product of negative economic value, the very existence of which creates unnecessary risks and the disposal of which is terribly expensive.

Beijing's ambition roils the waters in an East Asian environment that is already struggling with the questionable economic rationality and nonproliferation good sense of similar civil-nuclear ambitions elsewhere: in Japan's would-be plutonium economy, and in the Republic of Korea as it, too, debates such issues. The world most certainly does not need Beijing to raise tensions, and raise the stakes, in this fashion as the region grapples with such matters. Nor does the world need China's development of such a potent "expansion option" to further complicate negotiated nuclear arms reductions, including between the United States and the Russian Federation.

This report makes a number of suggestions about how to deal with this emerging problem, which we hope readers will carefully consider. (The report does not address the complexities of arms control negotiations with Russia, and the still more complex prospects with China, which could help head off the dangerous new arms race.) In our view, at the very least, it is time for leaders from around the Pacific Rim to engage with each other diplomatically as this report recommends about whether it is really a good idea for such an important, dynamic, and prosperous area of the world to further entangle itself with the production of additional tons and tons of the world's most dangerous material, or instead to seek a better alternative. The United States should work with the PRC, ROK, and Japan to forestall industrial-scale reprocessing, which would only make the entire region, and the world, less secure. While our leaders talk, moreover, we hope that all five nations will have the wisdom to pause the headlong rush into plutonium production, to give such diplomacy a chance to find more sensible answers.

This report deserves attention, and the issues it raises careful thought. We hope you will read it, and share it, with this in mind.

Christopher Ford
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Assistant Secretary 2018-21
Performed Under Secretary duties 2019-21
Administration of Donald Trump

Thomas Countryman
The Hon. Thomas Countryman
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Introduction

China's Civil Nuclear Sector: Plowshares to Swords?

Henry D. Sokolski

Although much has been said about the fusion of China's civilian and military sectors,[1] no detailed, unclassified analysis has been done of how Beijing's "peaceful" nuclear efforts might be exploited to make more nuclear warheads. Even the U.S. Department of Energy's own explanations of the export restrictions it imposed on "advanced" nuclear exports to China failed to discuss this.[2]

This volume is dedicated to clarifying just what the connection could be. Much of it focuses on China's advanced fast breeder reactor program and its related plutonium recycling efforts. As explained in this volume's first chapter, "How Many Nuclear Warheads China Might Acquire by 2030," the least burdensome way for China to achieve nuclear weapons parity with the United States is simply to use the weapons-grade plutonium that its planned "peaceful" fast breeder reactor and reprocessing programs will produce to make primaries for the two-stage thermonuclear weapons designs they already have perfected. By exploiting this weapons plutonium and the highly enriched uranium and tritium that China can easily access or make, Beijing by 2030 could conservatively assemble an arsenal of 1,270 warheads (nearly as many as the US currently has deployed on its intercontinental missiles).

Hui Zhang's, Greg Jones', and Frank Von Hippel's analyses in chapters two, three, and four make clear that China has the nuclear infrastructure and stockpiles to achieve this number with relative ease. If Beijing instead chooses to develop single-stage nuclear weapons using boosting, highly enriched uranium (HEU) or composite plutonium-HEU warhead designs, it could easily exceed this number by a factor of two or more.

None of China's "advanced" fast reactor systems are needed to meet China's energy or environmental requirements. As noted in David Von Hippel's analysis, China's advanced reactors and reprocessing are vastly uneconomical ways to produce nuclear power. Nor are they needed to make up for any foreseeable

1. See, e.g., Alex Stone and Peter W. Singer, "China's Military-Civil Fusion Strategy: What to Expect in the Next Five Years," *DefenseOne,* February 18, 2021, available at https://www.defenseone.com/ideas/2021/02/china-military-civil-fusion-strategy-next-five-years/172143; Elsa B. Kania and Lorand Laskai, "Myths and Realities of China's Military-Civil Fusion Strategy" (Washington, DC: Center for A New American Security, January 28, 2021), available at https://www.cnas.org/publications/reports/myths-and-realities-of-chinas-military-civil-fusion-strategy. and Bill Gertz, "Christopher Ford, State official, fights China technology theft," *The Washington Times*, October 2018, available at https://apnews.com/article/0cba7074875955fe8e905e2ea984b6c3.

2. See U.S. Department of Energy, DOE Announces Measures to Prevent China's Illegal Diversion of U.S. Civil Nuclear Technology for Military or Other Unauthorized Purposes," October 11, 2018, available at https://www.energy.gov/articles/doe-announces-measures-prevent-china-s-illegal-diversion-us-civil-nuclear-technology .

shortage of uranium. Compared with natural gas, hydro and renewables, which are cheaper still, investing now in commercial fast reactors makes no economic sense. As for abating carbon, China is planning for all of its power reactors, fast and thermal, to supply no more than 10 percent of China's electrical demand. Of that, less than a percent will likely be supplied by fast reactors.

Why, then, is China pushing ahead with advanced fast reactors and reprocessing? For much the same reason our own nuclear laboratories are — prestige. Faced with the economic facts, Germany, France, the UK, and Japan have all given up on the dream of recycling plutonium from spent reactor fuel in fast breeder reactors. China has not. What's also odd is that the operators of China's one, small, pilot reprocessing plant, who used to report on its annual performance to the International Atomic Energy Agency (IAEA), stopped doing so after 2017. If China's civil plutonium program is peaceful, it's difficult to understand why.

This raises another problem with China's "peaceful" plutonium program. Like all other reprocessing and enrichment programs elsewhere, it is not really possible to safeguard these activities in a fashion that can reliably assure timely warning of possible abrupt or incremental military diversions. As is explained in the two appended studies, the history of safeguarding reprocessing, in particular, has been punctuated with disturbing failures, which do not lend themselves to technical fixes.

What, then, does this recommend? Three things:

First, the United States should urge China to join the United States, as well as South Korea and Japan, in sharing information on their civil plutonium and enriched uranium holdings and production capacities. China stopped reporting on its plutonium separation activities in 2018 while South Korea, Japan, and the United States fully share information on their civilian nuclear fuel making activities privately with the IAEA. This information and China's should be made public. In addition, the United States and China should share information on their military plutonium and uranium holdings. The United States already shared this information in 1996 and 2001. China does not.

Second, the United States should explore with China, Japan, and South Korea the possibility of taking a plutonium production timeout. Japan, South Korea, and the United States should offer to delay their fast reactor and commercial plutonium programs if China would do likewise.

Third, regarding uranium enrichment, the United State and China should agree to cap their current enrichment capacities and place as much of them under international safeguards for as long as seems reasonable given projected, relatively flat commercial demand.

To date, the United States has not publicly made any of these proposals. It should. First, Washington needs to make sure China does not violate the terms of its nuclear cooperative agreement with the United States. Under this agreement, reached in 2015, China cannot reprocess US-origin spent fuel unless it has first met several conditions. The United States needs to know whether China has reprocessed any US-origin spent fuel or if it plans to do so.

Second, if Washington is serious about arms control and wants to reduce nuclear arms further, it needs to know what China is up to. Certainly, if China has a large fissile stockpile that it can expand dramatically relatively quickly, Russia is unlikely to agree to further major cuts. Also, it is unclear if it is in China's interest to ramp up its nuclear weapons production as quickly as it technically might. Doing so runs the risk of provoking the United States and China's neighbors, including Japan, South Korea, India and Russia. Does China understand this?

Third, trying to engage China diplomatically about its "peaceful" plutonium program makes sense irrespective of whether or not it agrees to share more information about it or to place the program on pause.

The economics of the program are clearly negative. Not allowing the IAEA to inspect or track it also is a bad look.

The U.S. Department of Energy has expressed interest in promoting fast reactor programs of its own. Congress has not funded the flagship US fast test reactor, though, at anywhere near what the Energy Department would like. South Korea has also placed its pyroprocessing efforts on financial hold and Japan has pushed the initial operating date for its large reprocessing plant off until 2023. Proposing a civil plutonium production timeout, it would make sense. If, however, China rejected the idea, that alone should set off alarms that otherwise might not go off.

Finally, it would be helpful to explore pausing reprocessing and expanding enrichment capacities to fortify international efforts to keep nuclear power as peaceful as possible, not just in East Asia, but in the Middle East, and globally. In this regard, focusing on China's program, in a nonthreatening way, is a sensible place to begin.

Chapter 1

How Many Nuclear Warheads China Might Acquire by 2030

Thomas B. Cochran and Henry D. Sokolski

Abstract

The U.S. Department of Defense determined last fall that China had a nuclear arsenal in the "low 200s," and that Beijing could "at least double" it by 2030. Subsequently, Admirals Charles A. Richard of Strategic Command and Phillip Davidson and John Aquilino of U.S. Indo-Pacific Command claimed that China could triple or quadruple its current arsenal by 2030. These estimates, however, fail to factor in China's planned "peaceful," "civil" nuclear program. In specific, they fail to mention China's plutonium fast breeder reactor program, which will be capable of producing a significant amount of weapons-grade plutonium. If one includes it and China's nonweaponized military stockpile of weapons-grade plutonium, China conservatively could obtain on the order of 1,270 warheads by 2030 — roughly as many as America currently has deployed on its intercontinental-range ballistic missile force. China has a variety of additional nuclear materials production options that could enable it to further increase this number by a factor of two or more. Production of weapons-grade plutonium from its "peaceful" fast reactor program, however, is the least burdensome approach to enlarge China's arsenal of advanced, two-stage thermonuclear weapons. What is troubling is China agreed to report annually to the IAEA on what China's civil plutonium holdings and production activities are but stopped doing so in 2017. The United States, which also files these reports, should also ask China why. In addition, and before China completes construction of its fast reactors and plutonium reprocessing plants, Washington should explore with Beijing, Tokyo, and Seoul the merits of agreeing to pause commercializing fast reactor fuel cycles, all of which are exceedingly uneconomic in comparison to other forms of nuclear and nonnuclear electricity production.

I. Overview

The projected number of nuclear weapons China might have by 2030 has grown in the last two years. In 2019, the Director of the Defense Intelligence Agency (DIA) said China might "at least double" its arsenal of nuclear weapons by 2030, which the Pentagon estimated in September of last year to be in the "low 200s."[3] That suggested China's arsenal might grow to as many as 500 warheads by 2030 "without new fissile production."[4] Three months later, in December of 2020, though, the Federation of American Scien-

3. See U.S. Department of Defense, *Military and Security Developments Involving the People's Republic of China 2020* (Washington, DC: Office of the Secretary of Defense, September 1, 2020), available at https://media.defense.gov/2020/Sep/01/2002488689/-1/-1/1/2020-DOD-CHINA-MILITARY-POWER-REPORT-FINAL.PDF.

4. See, Alex Ward, "China may double its nuclear arsenal in just 10 years. Don't panic.," *Vox*, September 2, 2020, avail-

tists (FAS) estimated that China had, not in the low 200s, but 350 nuclear weapons.[5] Finally, in February of 2021, Admiral Charles A. Richard, U.S. Commander of Strategic Command, wrote that the Chinese nuclear arsenal "is expected to double (if not triple or quadruple) over the next decade." More recently, Admiral Philip Davidson, head of U.S. Indo-Pacific Command, confirmed this projection. [6] His designated successor, Admiral John Aquilino, noted, however, that even if China quadrupled its current nuclear weapons arsenal, it would not surpass the number of nuclear weapons America currently deploys.[7]

This later projection makes sense if one adds the 350 nuclear weapons we now believe China has (based on unclassified estimates) to the roughly 480 weapons we believe China could make from the weapon-grade plutonium (WGPu) we believe it has stockpiled but not yet weaponized.[8]

All these projections currently, however, only look at existing "military" fissile stocks. If, in addition, one dials in the roughly 1,440 kgs of WGPu China is capable of producing from the two "civilian" breeder reactors is has under construction, and the 110 kgs of WGPu it could recover by processing blanket material from its small experimental fast breeder reactor, Beijing conservatively could acquire not "between 400 and 500 nuclear weapons,"[9] but most likely at least 1,270 nuclear warheads by 2030[10] — closing in on or exceeding the roughly 1,300 strategic warheads the United States currently has deployed on its intercontinental ballistic missiles.[11]

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able at https://www.vox.com/2020/9/2/21418252/china-military-report-nuclear-double Hans M. Kristensen, "DIA Estimates For Chinese Nuclear Warheads," *Federation of American Scientist*s, May 31, 2019, available at https://fas.org/blogs/security/2019/05/chinese-nuclear-stockpile/.

5. Hans M. Kristensen and Mark Korda, "Nuclear notebook: Chinese nuclear forces, 2020," *Bulletin of the Atomic Scientists*, December 7, 2020, available at https://thebulletin.org/premium/2020-12/nuclear-notebook-chinese-nuclear-forces-2020/. This estimate is comparable to the estimate of 360 nuclear warheads made by Hui Zhang, "China's nuclear force modernization," in Allison Pytlak and Ray Acheson ed., *Assuring destruction forever: 2020 edition*. June 2020, Reaching Critical Will, a project of the Women's International League for Peace and Freedom, available at https://www.reachingcriticalwill.org/images/documents/Publications/modernization/assuring-destruction-forever-2020.pdf

6. See, Admiral Charles A. Richard, "Forging 21st-Century Strategic Deterrence," *Naval Institute Proceedings*, February 2021, available at https://www.usni.org/magazines/proceedings/2021/february/forging-21st-century-strategic-deterrence and Caitlin McFall, "US losing military edge in Asia as China looks like it is planning for war: US Indo-Pacific Command chief," *Fox News*, March 10, 2021, available at https://www.foxnews.com/politics/us-losing-military-edge-in-asia-as-china-looks-like-planning-for-war-admiral.amp.

7. Sarah Cammarata, "Admiral nominated to lead Indo-Pacific forces contradicts current commander on Chinese nuclear stockpile," *Stars and Stripes*, March 23, 2021, available at https://www.stripes.com/news/pacific/admiral-nominated-to-lead-indo-pacific-forces-contradicts-current-commander-on-chinese-nuclear-stockpile-1.667015.

8. Here we assume China has 2.9 ± 0.6 tons of WGPu in weapons and available for weapons and 3 to 4 kilograms (kgs) of WGPu per warhead.

9. Alex Ward, "China May Double its nuclear arsenal in just 10 years. Don't panic.," *Vox.* September 2, 2020, available at https://www.vox.com/2020/9/2/21418252/china-military-report-nuclear-double.

10. Our estimate is $1,270 \pm 280$ warheads. For the benefit of those less familiar with statistics we can express this as between 990 and 1550 warheads.

11. The March 2020 START declaration for the United States shows 1,373 warheads on deployed ICBMs, deployed SLBMs and deployed heavy strategic bombers, where one nuclear warhead is counted for each heavy bomber. There are approximately 56 deployed strategic heavy bombers. See https://www.armscontrol.org/factsheets/Nuclearweaponswhohaswhat.

EXISTING PRC WGPu STOCKS 2021		
WGPu in kgs	Current number of warheads, assuming 3.5 kgs of WGPu/warhead primary	Additional warheads PRC could make with stockpiled WGPu assuming 3.5 kgs of WGPu/warhead primary
2,900	350	480
ADDITION "PEACEFUL" PRC WGPu STOCKS BY 2030		
WGPu in kgs	Additional warheads, assuming 3.5 kgs of WGPu/warhead primary	Total number of warheads by 2030, assuming 3.5 kgs of WGPu/warhead primary
1,550	440	1,270 (+/-275)

Our projections are conservative. The most contingent assumption is that China will follow through on the construction and planned operation of two additional, large fast breeder reactors and at least one nuclear fuel reprocessing plant, which it is building (but has not yet completed) to recover the WGPu from breeder reactors' used radial blanket fuel.

Our projections do not include the additional separated plutonium that might be produced in a second large demonstration reprocessing plant China has just begun constructing (which may come on line before 2030),[12] or the nuclear weapons China might produce using highly enriched uranium (HEU) exclusively. Nor do our projections consider China's ability to double the number of warheads by making composite cores (WGPu and HEU) in the thermonuclear primaries. Our projections excluded these options because they would entail new, untested weapons designs. Nor do our projections consider weapons that China might make from plutonium it could extract from the axial blankets in its planned fast reactors or from plutonium it could generate in its thermal power reactors (both heavy water and light water moderated). Extracting more plutonium from its thermal power reactors would require building additional fuel reprocessing capacity. If one dials in these additional nuclear weapons materials' sources, though, the total number of nuclear warheads China might make by 2030 increases by a factor of at least two or more.

None of this is inevitable. China has only just begun construction of its first large, 200 tons per year (t/y) spent reactor fuel reprocessing plant. Nor has it completed work on its two 600 MWe fast breeder reactors. These plants are projected to begin operation in three and five years. More important, it is debatable that it is in China's interest to ramp-up its nuclear arsenal so aggressively. China has actually complained about Japan's ability to make more than 2,500 nuclear weapons from the separated civilian plutonium Japan has on its soil. China also has objected to Japan's plans to start operating its Rokkasho commercial nuclear fuel reprocessing plant in 2023.[13] With a design capacity of 800 t of spent fuel per year and operating at an assumed 75 percent capacity factor, Rokkasho could separate at least 1,200 bombs' worth of plutonium or more a year, assuming 5 kgs of reactor-grade plutonium (RGPu) per warhead.

So far, the United States has quietly persuaded Japan to put off opening this large plant, arguing that its operation would likely upset China as well as South Korea (whose nuclear scientists also want to recycle plutonium). If Beijing proceeds with its reprocessing expansion (in 2025 for the first plant and sometime before 2030 for the second plant) and its two 600 MWe fast reactors (projected to come on line in 2023

12. See Hui Zhang, "China starts construction of a second 200 MT/year reprocessing plant," International Panel on Fissile Materials, March 21, 2021, available at http://fissilematerials.org/blog/2021/03/china_starts_construction.html.
13. See China Arms Control and Disarmament Association, China Institute of Nuclear Information and Economics, "Study on Japan's Nuclear Materials," September 2015, available at http://fissilematerials.org/library/cacda15.pdf.

and 2026), then it must worry that Japan will proceed with its reprocessing efforts too. This would result in Japan stockpiling many more thousands of nuclear weapons worth of explosive plutonium and also would likely prompt South Korea to proceed with a plutonium recycling program of its own.

How China would respond is anyone's guess but if it chose to go toe-to-toe with its neighbors, China could easily be seen as a nuclear provocateur by India, Russia, and the United States. How this is China's national security interest is, at best, unclear. Nor is there an economic or environmental case for making or using plutonium-based fuels. Much cheaper uranium is and will be plentiful throughout this century.[14] Nor does recycling ease the management of spent reactor fuel.[15] Nuclear scientists and industry, of course, all want their governments to subsidize large nuclear "commercialization" projects but those using plutonium-based fuel can and should be put off.

This, then, brings us to China's surplus uranium enrichment capacity, which is large and could be used to make uranium-fueled bombs or composite plutonium-uranium cores. As noted in the analysis below, China could use only a portion of its unsafeguarded enrichment capacity to make many hundreds of additional single-stage weapons with yields in the scores of kilotons, or higher. Again, there's hardly any economic justification for having so much uranium enrichment capacity. Currently, there is more than enough uranium enrichment capacity within China to meet its projected power reactor requirements. Globally, there is enough to service not just China's, but Japan's, South Korea's, Europe's, and America's commercial needs as well.

What, then, does this study recommend? Three things:

- First, the United States should urge China to join the United States, as well as South Korea and Japan, in sharing information on their civil plutonium and enriched uranium holdings and production capacities. China stopped reporting on its plutonium separation activities in 2018 while South Korea, Japan, and the United States fully share information on their civilian nuclear fuel making activities privately with the IAEA. This information and China's should be made public. In addition, the United States and China should share information on their military plutonium and uranium holdings. The United States already shared this information in 1996 and 2001. China does not.

- Second, the United States should explore with China, Japan, and South Korea the possibility of taking a plutonium production timeout. Japan, South Korea, and the United States should offer to delay their fast reactor and commercial plutonium programs if China would do likewise.

- Third, regarding uranium enrichment, the United State and China should agree to cap their current enrichment capacities and place as much of them under international safeguards for as long as seems reasonable given projected, relatively flat commercial demand.

14. See Bunn, Matthew, Hui Zhang, and Li Kang. "The Cost of Reprocessing in China." Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School, January 2016, available at https://www.hks.harvard.edu/publications/cost-reprocessing-china.
15. See National Research Council 2008. *Review of DOE's Nuclear Energy Research and Development Program* (Washington, DC: The National Academies Press, 2008), pp. 73-76, available at https://www.nap.edu/cart/download.cgi?record_id=11998&file=73-76.

II. Background

China's nuclear weapons program is shrouded in secrecy. Unlike the United States, China has never publicly declared the size of its nuclear weapons stockpile, the number of delivery systems of various types, e.g., ICBMs, SLBMs, bombers, and tactical missiles, or the size of the fissile material inventories, i.e., plutonium and highly enriched uranium (HEU), both in weapons and available for weapons. China has not revealed how it produces tritium for weapons since the closure of its plutonium production reactors. China is not a participant in the New START Treaty. One can make estimates from what is known, as is done here, but it should be a U.S. government policy objective be to seek greater transparency regarding China's nuclear weapons-related materials and production capacities.

That said, if we stick to what we know, or what we think we know, we draw the following conclusions:

- China has approximately 350 nuclear warheads, of which roughly 272 are for delivery by more than 240 operational land-based ballistic missiles, 48 sea-based ballistic missiles, and 20 nuclear gravity bombs assigned to bombers.[16]
- China has an estimated 2.9 ± 0.6 t of stockpiled WGPu. This would be enough to make 830 ± 210 nuclear weapons or more, assuming 3.5 ± 0.5 kg WGPu per device.
- China also has stockpiled 14 ± 3 t of weapon-grade HEU in weapons and available for weapons — enough to make 930 ± 370 nuclear warheads assuming 15 ± 5 kg of HEU per warhead.[17]
- China can more rapidly expand its HEU production capacity than it can expand its WGPu production capacity. The later would require China to build more spent reactor fuel reprocessing capacity. It is currently doing so by building two 200 t/y plants. One is expected to come on line in 2025, the other sometime before 2030.
- Another option for doing so is for China to buy the large 800 t/y spent reactor fuel reprocessing plant that it has been in negotiations with France to buy now for several years. This plant would enable China to produce some 1,200 more nuclear weapons' worth of RGPu/y. So far, the French and Chinese have been unable to finalize the deal.
- Thus, to expand its arsenal of two-stage thermonuclear weapons (where the primary would use plutonium), the availability of WGPu is the key material that limits the rate of increase in the size of China's high-yield thermonuclear warhead arsenal ideal for use on its intercontinental ballistic missiles (ICBMs and SLBMs).
- The availability of tritium for boosting thermonuclear warhead primaries is assumed not to be a pacing item, although there is no public information on where and how China currently produces tritium for weapons.
- All of China's dedicated military plutonium production reactors and military chemical separation plants appear to be permanently shut down.
- Should China seek to increase its military WGPu stockpile, it is likely to use its civil reactors to acquire the additional plutonium. In order of priority, China first would reprocess the irradiated

16. See note 2 above.
17. Hui Zhang, *China's Fissile Material Production and Stockpile,* IPFM Research Report No. 17, 2018 (Princeton, NJ: Princeton University), available at https://www.belfercenter.org/publication/chinas-fissile-material-production-and-stockpile.

blanket material from the two 600 MWe fast breeder reactors it is now building (projected to come on line in 2023 and 2026). If additional WGPu is desired, the next source would be its heavy water reactors, and lastly it could turn to its light water reactor (LWR) fleet.

- By 2030, China could recover at least 1.2 - 2.0 t of WGPu by reprocessing breeder reactor blanket fuel assemblies, but not touching axial blanket material.[18]
- Used nuclear fuel reprocessing capacity is the pacing item limiting the recovery of WGPu from civil reactors.
- Although there would be a considerable reduction in yield-to-weight and yield-to-volume, single stage fission weapons and even two-stage thermonuclear weapons can be made without WGPu by relying solely on HEU, RGPu, or a combination of both. China is therefore essentially unconstrained in the rate of production of bomber weapons and lower yield ballistic missile warheads.

III. Frequently Asked Questions

<u>Q1. Is China currently pursuing a minimal nuclear deterrence policy?</u>

In the 1990s China clearly professed a minimal nuclear deterrence policy. China's economy was weaker than it was today. The United States and Russia had comparatively far more deployed and reserve nuclear weapons and fissile material for weapons. To make up for this difference, China relied on underground siting of its ICBMs and probably targeted U.S. cities.

Today, China's profession of its minimal deterrence strategy is less clear. It was reported that China has launch-on-warning and launch-on-alert capabilities as well as higher accuracy, lower-yield nuclear missile systems that are suitable for hitting not just area targets (cities), but military point targets.

<u>Q2. How many nuclear weapons do experts believe the Chinese have today? What uncertainties do they assign to their estimates? What is the basis for these uncertainties?</u>

The FAS, a non-government organization that carefully tracks nuclear weapon programs globally, estimates that China "has a produced a stockpile of approximately 350 nuclear warheads, of which roughly 272 are for delivery by more than 240 operational land-based ballistic missiles, 48 sea-based ballistic missiles, and 20 nuclear gravity bombs assigned to bombers. The remaining 78 warheads are intended to arm additional land- and sea-based missiles that are in the process of being fielded."[19] The U.S. Defense Intelligence Agency (DIA) in 2019 estimated that China had a nuclear arsenal in the low 200s, roughly FAS's estimate at the time.[20] It appears from the FAS analyses, historically various U.S. intelligence agencies and elements within the Department of Defense (DOD) have not always been consistent in their estimates of the size of the Chinese nuclear arsenal, and in DIA's earlier projections have not always been consistent with its subsequent estimates. In other words, it appears that the U.S. intelligence community may not have a good handle on the size of the Chinese nuclear arsenal or China's nuclear weapons plans for the

18. See Table 1.01 below. Totals have been rounded.
19. Hans M. Kristensen and Mark Korda, "Nuclear notebook: Chinese nuclear forces, 2020," *Bulletin of the Atomic Scientists*, available at https://thebulletin.org/premium/2020-12/nuclear-notebook-chinese-nuclear-forces-2020/.
20. Hans Kristensen, "DIA Estimates For Chinese Nuclear Warheads," Federation of American Scientists, May 31, 2019, available at https://fas.org/blogs/security/2019/05/chinese-nuclear-stockpile/.

future. Nevertheless, the FAS now estimates the current size of the Chinese nuclear arsenal is in the range of about 300 to 350 nuclear warheads.[21]

Q3. Is China now attempting to acquire a much larger nuclear arsenal, on par with, or exceeding, that of the United States and Russia?

Since the 1990s, China's economy has grown considerably—to the point that it rivals the size of the U.S. economy. Under the leadership of Xi Jinping, who became president of the People's Republic of China (PRC) in 2013, is the head of the Chinese Communist Party and paramount leader of China, China's goal is to displace the United States as the most powerful country in the world. To achieve this goal, it may believe it will need a nuclear arsenal as large or larger than that of the United States and Russia, i.e., an arsenal in five to ten years numbering in the thousands, rather than the hundreds of warheads. Its options are to increase the size of its own arsenal or wait until the United States and Russia negotiate a reduction of their nuclear arsenals. To date, China has been unwilling to enter arms control negotiations with the United States and Russia that could place limits on its own nuclear arsenal.

In 2019, the head of the Defense Intelligence Agency (DIA) stated that the Chinese nuclear weapons stockpile will "at least double" over the next decade.[22] A mere doubling of its stockpile would not put China's nuclear arsenal on par with that of the United States or Russia. A further increase several times more could do so.

Q4. Does China have a breakout strategy to increase the size of its nuclear arsenal? If so, does this strategy include using some of its civilian nuclear facilities to produce fissile material for weapons?

Officials in Beijing continue to insist that China has such a small arsenal, it should not be asked to limit it at this time. On the other hand, commentators in Chinese official newspapers have argued that China needs 1,000 nuclear weapons to deter the United States.[23] China also has explicitly called for a fusion of its civilian and military nuclear efforts. In the United States today, the nuclear weapons program is almost entirely separate from its civil nuclear power program. A notable exception is that tritium for nuclear weapons in produced in civil reactors. Chinese nuclear activities are not so clearly segregated. Given the size and orientation of China's civilian nuclear program to plutonium fuel cycles and large uranium enrichment plants, there is increasing uncertainty as to what China might do to mobilize and exploit this "peaceful" nuclear infrastructure for military purposes.

Q5. What materials matter most for nuclear weapons?

Were China to substantially increase the size of its nuclear weapon arsenal, China most likely would need to acquire additional stocks of plutonium, HEU, and tritium. Although typical thermonuclear weapon designs contain some five or more times as much HEU relative to plutonium, the pacing item for expanding China's arsenal of two stage thermonuclear warheads would be plutonium, not HEU for two reasons. First,

21. See note 14 above.
22. See note 15 above.
23. See Yew Lun Tian, "China needs more nuclear warheads: Global Times editor," *Reuters*, May 8, 2020, available at https://www.reuters.com/article/us-china-usa-war/china-needs-more-nuclear-warheads-global-times-editor-idUSKBN22K1EE.

China already has the capacity to make massive amounts of HEU but relatively no confirmed capacity to make WGPu in reactors dedicated for this purpose. Second, China will likely want plutonium to make higher yield-to-weight and higher yield-to-volume thermonuclear weapons for intercontinental missiles.

As for tritium, China has and can get all that it needs. Despite its radioactive decay with a half-life of 12.3 years, tritium can be readily made in military or civil nuclear reactors and should not be a constraint on expanding the weapon arsenal.

Although there would be a reduction in yield-to-weight and yield-to-volume, single stage fission weapons and even two-stage thermonuclear weapons can be made without WGPu by relying solely on HEU, RGPu, or a combination of both. As China modernizes its missiles to carry multiple warheads, it can produce the massive blast effects of a large-yield weapon by laying down much smaller yield multiple warheads. Bottom line: China is essentially unconstrained in the rate of production of bomber weapons, including bombs for strategic bombers and lower yield ballistic missile warheads.

<u>Q6. How much fissile material do experts believe the Chinese have stockpiled for weapons? What uncertainties do they assign to their estimates? What is the basis for these uncertainties? What is the range of surplus weapons plutonium and uranium stockpiled available for use in new weapons?</u>

Non-government best estimates of the Chinese military plutonium stocks have ranged from 1.8 t to 4.35 t with large uncertainties. [24] The best analyses are by Hui Zhang, whose latest estimate is 2.9 ± 0.6 t of WGPu.[25] The uncertainty "mainly come from the assumptions concerning the phase-out of plutonium production during the 1980s.[26]

Assuming 3.5 ± 0.5 kg of WGPu per thermonuclear warhead, this would be sufficient for about 830 ± 210 warheads. Assuming Hui Zhang's analysis is correct, China would have sufficient military plutonium stocks to double its nuclear arsenal over the next decade, recalling, as indicated above, that in 2019 the head of DIA reportedly stated that the Chinese nuclear weapons stockpile will "at least double" by 2030.

Hui Zhang estimates China currently has 14 ± 3 t of weapon-grade HEU available for weapons.[27] Assuming 20 ± 5 kg of HEU per thermonuclear warhead, this would be sufficient for 930 ± 370 thermonuclear warheads. 10 to 15 kg of HEU would likely be used to produce single-stage weapons with yields of a few tens of kilotons and more than 30 kg of HEU would probably be used to produce weapons with yields in the range of 50 to 100 kilotons.[28]

24. Hui Zhang, "China's Fissile Material Production and Stockpile," available at https://www.belfercenter.org/publication/chinas-fissile-material-production-and-stockpile.
25. Hui Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities," paper prepared for the Nonproliferation Policy Education Center (NPEC), June 23, 2020, p. 2., available at http://npolicy.org/article_file/Hui_Zhang_Paper.pdf.
26. Hui Zhang, "China's Fissile Material Production and Stockpile," available at https://www.belfercenter.org/publication/chinas-fissile-material-production-and-stockpile.
27. Hui Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040, p. 4, available at http://npolicy.org/article_file/Hui_Zhang_Paper.pdf.
28. Thomas B. Cochran and Christopher E. Paine, "The Amount of Plutonium and Highly Enriched Uranium Needed for Pure Fission Nuclear Weapons," (Washington, DC: Natural Resources Defense Council, Revised 13 April 1995), Figure 2. Such estimates are not an exact science, as the amount of fissile material used would depend not only on the technical sophistication of the warhead design, but also on considerations such as the desired weight and size of the weapon, i.e., yield-to-weight and yield-to volume considerations.

Q7. How much of the future plutonium, HEU, and tritium production might be produced in facilities that might be viewed as civil facilities?

There are no known military plutonium production reactors operational today. It is therefore likely that beyond existing stocks, any new plutonium for weapons produced in the next decade will come from what are traditionally viewed as civil reactor facilities. There is one caveat here. China has attempted to build and operate an underground plutonium production reactor, so it cannot be ruled out that such a plant exists today (see Q10 below).

Beyond existing stocks, additional HEU for weapons will come from what are traditionally considered to be dual purpose (civil and military) uranium enrichment facilities.

There are no treaty agreements, e.g., the Non-Proliferation of Nuclear Weapons Treaty (NPT), or international agreements, e.g., IAEA safeguards agreements, prohibiting the use of civil reactors for the production of tritium for nuclear weapons.

Q8. How much plutonium might China produce by 2030?

The plutonium production reactors at China's two known military plutonium production sites, Jiuquan Atomic Energy Complex (Plant 404) and Guangyuan plutonium-production complex (Plant 821), are believed to have ceased production of plutonium around November 1986 and 1984, respectively.[29] It is reasonable to assume these reactors could not or will not be restarted at this late date. Therefore, it is reasonable to assume that beyond existing stocks, if China desired additional plutonium for weapons prior to 2030, it could turn to its civil reactors for additional plutonium. Estimates below indicate that China could readily produce on the order of 1.2 to 2 t of additional WGPu by 2030 from fast breeder reactors. Additional WGPu (several times as much) could be recovered from civil reactor spent fuel, but this would require substantial increase in nuclear fuel reprocessing capacity.

Q9. Discuss what challenges China would face to reprocess all of the materials it might want to in a "crash" ramp up scenario. Would it need to build additional reprocessing facilities? What might this entail?

All of China's known chemical separation plants have been shut down for years. China has a pilot reprocessing plant that is believed to be dedicated to reprocessing spent fuel from the Daya Bay Nuclear Power Plant, the site of two 984 MWe LWR. China also is building reprocessing plants with a capacity of 200 tons of heavy metal per year (tHM/y) each. The first is expected to come on line in 2025, the second sometime before 2030. These plants may be fully utilized separating plutonium to make mixed-oxide (MOX) fuel for the two 600 MWt fast breeder reactors under construction.

China has pursued the purchase of an 800 tHM/y civil reprocessing plant from France. If a plant of this size is built and operated at an average 75 percent capacity factor, it could recover on the order of 6 t/y of plutonium (or 1,200 bombs' worth of RGPu assuming 5 kgs per warhead and that the spent fuel processed contains approximately one percent plutonium).

29. Hui Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040, p.. 4, available at http://npolicy.org/article_file/Hui_Zhang_Paper.pdf.

Q10. What types of military production reactors does China have; what are their years of service and estimated capacity factors? Are there any such facilities now under construction?

Two Chinese military plutonium production reactors, both graphite-moderated water-cooled reactors, have been identified in the unclassified literature. One production reactor is at the Jiuquan Atomic Energy Complex (Plant 404) located 40° 13' 22.76" N; 97° 21' 21.09" E, in Gansu Province.[30] The second reactor (at 32° 29' 44.6" N; 105° 35' 24.5E), is at the Guangyuan nuclear complex (Plant 821) about 24 km WNW of Guangyuan in Sichuan Province.[31]

Hui Zhang has referenced a Chinese press report regarding an unfinished underground Fuling plutonium production complex, the so-called "Plant 816" in Sichuan province.[32] Plant 816 was an effort to build an underground light-water cooled, graphite-moderated plutonium production reactor with a power of 600 MWt.[33] Construction of Plant 816 was initiated in February 1967 and terminated in 1984.[34]

The lack of knowledge of the actual thermal power ratings of the Jiuquan and Guangyuan reactors, and the lack of assurance that there is not a still secret underground plutonium production facility are the greatest impediments to understanding the size of the inventory of plutonium in and available for Chinese nuclear weapons.

Hui Zhang reports the reactor at Jiuquan operated from December 1966 to 1984.[35] The reactor at Guangyuan started operation near the beginning of 1974. When the Guangyuan reactor ended production is unknown but it is assumed to have been sometime in the late-1980s or early 1990s.

Q11. What are China's military chemical separation facilities, their capacities, and their years of service? Are there any such facilities now under construction?

China operated three military chemical separation plants all of which are believed to be shut down. These are the Jiuquan intermediate pilot plant (1968 to early-1970s), the Jiuquan chemical separation plant (1970-ca. 1987), and the Guangyuan chemical separation plant (1976-ca. 1987). The capacity of these plants is assumed to have been matched approximately to the rate of plutonium production from the production reactors at these sites.

30. Robert S. Norris, Andrew S. Burrows and Richard W. Fieldhouse, *Nuclear Weapons Databook, Volume V, British, French and Chinese Nuclear Weapons* (Boulder; Westview Press, 1994), p. 339.

31. Hui Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities," p. 2. Hui Zhang, "China's Fissile Material Production and Stockpile," available at https://www.belfercenter.org/publication/chinas-fissile-material-production-and-stockpile.

32. Hui Zhang, "China's Fissile Material Production and Stockpile," available at https://www.belfercenter.org/publication/chinas-fissile-material-production-and-stockpile.

33. Ibid.

34. Ibid.

35. Ibid.

Q12. What Chinese fissile production-related facilities are not clearly dedicated for military purposes that could be so used?

Plutonium Production Facilities

While there is no public evidence that it intends to do so, China could produce plutonium for weapons by reprocessing spent fuel from civil reactors. Assuming the objective would be to recover WGPu, the order of preference would probably be:

a) fast breeder reactor blanket material;

b) heavy water reactor spent fuel;

c) low-burnup spent fuel discharged from LWRs at the time of the first refueling.

Fast Reactors

The Chinese Experimental Fast Reactor (CEFR) is a 65 MWt, 20 MWe reactor located at (39º 44' 26" N, 116º 1' 51" E), about 20 miles southwest of Beijing. It achieved criticality in July 2010 and was connected to the grid in July 2011. Fuel for the first core consisted of HEU (64.4% enriched) and it seems to still be using HEU in 2020. Later fuel loadings may be MOX fuel: 219.2 kg of fissionable material: --121.6 kg Pu (93.2 kg Pu-239); -- 97.6 kg U-235 (30% enriched uranium).[36]

Two commercial-size Chinese Fast Reactors (CFRs) are under construction at Xiapu in Fujian province (26º 48' 13" N, 120º 9' 18" E). These CFR-600s are 1500 MWt, 600 MWe reactors. Construction of the CFR-600s began in December 2017 and December 27, 2020, respectively. Commissioning of the first reactor is expected in 2023; the second in 2026. The maximum burn up is about 100 MWd/kgHM. They will be fueled using HEU supplied by TVEL in Russia.[37] Later they would be fueled by MOX, where the plutonium is recovered at the 200t/yr reprocessing plant. Both the MOX fabrication plant and the reprocessing plant are located at Jinta, Gansu.[38]

Xiapu in Fujian province is also reported to be the site for the prototype so-called travelling-wave reactor TWR-P. In December 2013, a US Federal Register notice said that the USA had negotiated an agreement with China "that would facilitate the joint development of TWR technology" from TerraPower, including standing wave versions of it. In September 2015, CNNC and TerraPower signed an agreement to work towards building a prototype 600 MWe TWR unit in China, apparently over 2018 to 2023.[39] On October 11, 2018, the U.S. Department of Energy effectively killed this project by promulgating a regulation pro-

36. "China's Fast Breeder Reactor (FBR) Program," Nuclear Threat Initiative, updated February 6, 2004, available at https://web.archive.org/web/20080208125200/http://www.nti.org/db/china/fbrprog.htm. The core has also been reported as containing 150 kg Pu (98 kg Pu-239). *World Nuclear News*, "China starts building second CFR-600 fast reactor," *World Nuclear News*, December 29, 2020, available at https://world-nuclear-news.org/Articles/China-starts-building-second-CFR-600-fast-reactor.
37. "CFR-600," Wikipedia, last modified January 15, 2021, available at https://en.wikipedia.org/wiki/CFR-600#:~:text=The%20CFR%2D600%20is%20a,Xiapu%20fast%20reactor%20pilot%20project.
38. Hui Zhang, "China is speeding up its plutonium recycling programs," *Bulletin of the Atomic Scientists*, Vol.76, No.4, 2020, available at https://www.tandfonline.com/doi/abs/10.1080/00963402.2020.1778372?journalCode=rbul20.
39. "Fast Neutron Reactors," World Nuclear Association, updated December 2020, available at https://www.world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.

hibiting the transfer of U.S. advanced reactor technology to China.[40]

A commercial-scale fast breeder, the CFR1000, has been proposed to have a capacity of 1,000-1,200 MWe. An earlier design of the CFR1000 was a 2,500 MWt pool-type reactor using MOX fuel. Subject to a decision to proceed, construction could start in December 2028, with operation from about 2034.[41] That design will use metal fuel and 120-150 GWd/t burnup.

Heavy Water Reactors

Qinshan Phase III, units 1&2, are CANDU-6 pressurized heavy water reactors (PHWR). The Qinshan site is located in Haiyan County ((30° 29' 59" N, 120° 57' 0" E), Zhejiang Province, on the shore of Hangzhou Bay off the East China Sea and approximately 126 km south west of Shanghai. They are each designed to operate in 2064 MWt, 528 MWe gross, 677 MWe net. They achieved first criticality on September 21, 2002, and January 18, 2003, and were commissioned (began commercial operation) on December 31, 2002 and July 24, 2003, respectively. The two PHWRs have each operated at high cumulative capacity factor, 0.9, over their lifetime (from the year following criticality through 2019), [42] reflecting the fact that they do not have to shut down for refueling.

The CANDU-6 reactor core has 380 fuel channels contained in and supported by a horizontal cylindrical vessel known as the calandria.[43] There are 12 fuel bundles per channel, each containing 21.4 kg of natural uranium oxide (UO_2) fuel. Typically, in a CANDU-6 about 10 fuel channels per week are refueled, and either four or eight of the fuel bundles in a channel are replaced during a refueling operation.[44]

Light Water Reactors

China had 49 operational reactors in 2020, of which 46 were LWRs.[45] Many of the LWRs were designed by foreign nuclear vendors and all contain some technology from foreign vendors. China has been moving toward a goal of supplying 100 percent of the nuclear components from domestic suppliers.

40. U.S. Department of Energy, "DOE Announces Measures to Prevent China's Illegal Diversion of U.S. Civil Nuclear Technology for Military or Other Unauthorized Purposes," October 1, 2018, available at https://www.energy.gov/articles/doe-announces-measures-prevent-china-s-illegal-diversion-us-civil-nuclear-technology.
41. See note 34 above.
42. "QINSHAN 3-1," International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS), updated February 16, 2021, available at https://pris.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=69; and "QIN-SHAN 3-2," IAEA PRIS, updated February 16, 2021, available at https://pris.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=840.
43. Zhang Yanfa and B.A. Shalaby, "Introduction to the Qinshan Phase III CANDU Nuclear Power Plant," CANTEACH, 1999, available at https://canteach.candu.org/Content%20Library/20054402.pdf.
44. *CANDU 6 Technical Summary*, CANTEACH, May 2005, available at https://canteach.candu.org/Content%20Library/CANDU6_TechnicalSummary-s.pdf.
45. "Country Statistics for People's Republic of China," IAEA PRIS, updated February 16, 2021, available at https://pris.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=CN.

Q13. What amount of WGPu is currently available from these sources and their projected annual production? Identify similar sources from reactors under construction. What international agreements, e.g., with the International Atomic Energy Agency (IAEA) or nuclear supplier nations, that are intended to prevent the use of civil reactors or civil nuclear fuel reprocessing plants for military purposes?

Fast Breeder Reactors

The CEFR is 65 MWt and the CFR-600s are 1500 MWt each. Here, as other analysts have done, we will scale from a WGPu production estimate for the PFBR, a 1250 MWt sodium-cooled fast breeder reactor in India. Alexander Glaser and M.V. Ramana estimate that the PFBR, using MOX fuel in the core and operation at a capacity factor of 0.75, will produce 92.4 kg WGPu/y in the radial blanket and 52.0 kg WGPu/y in the axial blankets.[46] Scaling by (1500/1250 =) 1.2, the CFR-600 operating at the same capacity factor of 0.75 and using MOX fuel in the core will produce an estimated 173 kg WGPu/y in the radial and axial blankets combined, of which 111 kg WGPu/y are produced in the radial blanket.

The first core of the first CFR-600, and possibly the first core of the second CFR-600, will be fueled with enriched UO_2, rather than MOX. In Table 1.01 we therefore reduce the rate of production for the first three years by five percent. The low end of the range assumes the reactors operate at a capacity factor of 0.65 and only the plutonium from the CFR-600 radial blankets is recovered for the weapons stockpile, and the upper limit assumes a capacity factor of 0.75 and the WGPu from the radial and both axial blankets is recovered. We assume that the MOX cores of these reactors were fueled with RGPu recovered from reprocessed LWR spent fuel, and the WGPu bred in the reactor blankets is not recycled but could be reserved for weapons.

46. Alexander Glaser and M. V Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science and Global Security*, 15:85-105, 2007, Table 2, p. 94, available at https://www.tandfonline.com/doi/abs/10.1080/08929880701609154.

Table 1.01: WGPu recovered from the blanket material in Chinese fast breeder reactors. Totals should be rounded.

Year	CEFR (kg WGPu)	CFR-600s) (kg WGPu)	Annual Total (kg WGPu)	Cumulative (kg WGPu)
2012-2020	45 - 56			45 - 56
2021	5 – 7		5 – 7	50 - 63
2022	5 – 7		5 – 7	55 - 70
2023	5 – 7		5 – 7	60 - 77
2024	5 – 7	91 - 164	96 - 171	156 - 248
2025	5 – 7	91 - 164	96 - 171	252 - 419
2026	5 – 7	91 - 164	96 - 171	348 - 590
2027	5 – 7	187 - 337	192 - 344	540 - 934
2028	5 – 7	187 - 337	192 - 344	732 - 1,278
2029	5 – 7	187 - 337	192 - 344	924 - 1,622
2030	5 – 7	192 - 346	197 - 353	**1,121 - 1,975**
		Total	**95 - 126**	**1,026 - 1,849**

Heavy water reactors

The heavy water reactors in China are Canadian designed CANDU reactors under IAEA safeguards. Therefore, the used fuel cannot be reprocessed to recover plutonium for weapons without violation of China's agreement with the IAEA and Canada. Also, China currently does not have adequate nuclear fuel reprocessing capacity to process the large amount of spent CANDU fuel to obtain significant amounts of WGPu. Thus, while the following calculations show how much WGPu could be produced in theory, it is unlikely that China will seek WGPu from its CANDU reactors.

Under normal operating conditions a CANDU reactor is a relatively sparse generator of RGPu as a weight percent of its used fuel. To obtain 800 kg of RGPu (at 27 percent Pu-240) over 200 tons of irradiated CANDU fuel (over 10,000 spent fuel bundles) would have to be reprocessed.[47] The civil demonstration reprocessing plant under construction near Jinta in Gansu province, has a rated capacity of 200 t/y.

A typical fuel burnup attained in the CANDU-6 is 7,500 MWt-d/tHM.[48] If fueled with natural uranium

47. J.J. Whitlock and A.G. Lee, "CANDU: Setting the Standard for Proliferation Resistance of Generation III and III+ Reactors," IAEA-CN-164-5P07, available at https://www-pub.iaea.org/MTCD/Publications/PDF/P1500_CD_Web/htm/pdf/poster/5P07_J.%20Whitlock.pdf.
48. Ben Rouben, "CANDU Fuel-Management Course," CANTEACH, March 1999, available at https://canteach.candu.org/Content%20Library/20031101.pdf.

(Nat-U), the spent fuel contains approximately 0.5 percent RGPu, or about one-half the concentration of RGPu in LWR spent fuel. To produce WGPu in the CANDU it would have to operate at about 1,000 MWt-d/tHM, in which case the concentration of WGPu in the spent fuel would be 7.5 time lower, or about 0.067 percent. Thus, reprocessing such low-burnup spent fuel at the 200 t/y demonstration reprocessing plant under construction near Jinta in Gansu province, operating at an assumed capacity factor of 75 percent, on the order of 100 kg of WGPu could be recovered per year.

The Qinshan Phase III, Units 1 & 2, CANDU-6 reactors, which are each rated at 2064 MWt, are assumed to continue to operate at their historical cumulative capacity factor of 90 percent. Thus, each could each produce about 540 kg of WGPu per year. Assuming they were both used to produce WGPu beginning in 2023, then by the end of 2030, together they could produce approximately 8,670 kg of WGPu. When added to the WGPu from the two fast reactors the total estimated WGPu production through 2030 would be 9,950 kg to 10,300 kg. However, this would require far more spent fuel reprocessing capacity than China has contemplated.

Alternatively, if the two CANDU-6 reactors operated at a burnup of 2,000 MWt-d/tHM for nine months, they could produce 1,018 kg of FGPu containing 9.8 percent Pu-240. This could be blended with 1,278 kg of super-grade Pu, the lower end of the estimated WGPu produced in the two fast reactors by 2030, to make about 2,300 kg of 6 percent Pu-240 WGPu. However, since China lacks reprocessing capacity, it is most likely that China would not produce super-grade Pu in the fast reactor blankets. Rather China would leave the radial blankets in the reactor for a period twice as long, thereby doubling the plutonium concentration and recovering WGPu (something close to 6 percent Pu-240).

Clearly, the bottleneck in producing additional WGPu by processing CANDU fuel is the lack of spent fuel reprocessing capacity. Also, there may be restrictions imposed by IAEA safeguards agreements or China-Canadian bilateral agreement(s) covering the CANDU reactors.

Gregory Jones has made a similar estimate of the amount of WGPu (at 6 percent Pu-240) that could be produced when operating at 1,200 MWt-d/tHM, compared to operating at 7,000 MWt-d/tHM.[49] Jones concludes:

> ". . .this could not be done for the entire reactor, since it would require using 5.8 times as much fuel per year and the reactor's refueling machine could not operate quickly enough. If this rapid refueling were limited to only one-eighth of the core, it would be feasible. Each reactor would then produce 67 kg WGPu per year. The plutonium would be at a concentration of only 1 kilogram per metric ton, so reprocessing the low burnup fuel from both reactors would require 134 metric tons per year of reprocessing capacity. This would be a significant fraction of China's reprocessing capacity. Finally, as was noted by von Hippel and Takubo, China's peaceful use agreement with Canada for these reactors requires Canada's permission to carry out the reprocessing, which may deter China from taking this action."[50]

Light Water Reactors

A report by Lawrence Livermore National Laboratory (LLNL) and Stanford University, "Verifying the Agreed Framework," April 2001, devotes a chapter to how the Democratic People's Republic of Korea

49. Gregory S. Jones, "China's Current Stocks of Separated Plutonium and Possible Growth to 2040," September 10, 2020.
50. Ibid.

(DPRK) could exploit LWRs to obtain plutonium for weapons.[51] One of the scenarios for obtaining FGPu from LWRs involves "short cycling," that is operating the reactor at a reduced burnup:[52]

> In the event of overt short-cycling of the reactor with a goal to obtain plutonium with 90 percent 239Pu, burnup would be limited to no more than about 7 Wd/kg, limiting the reactor cycle time to approximately 9 months. Assuming an industry average of 40 days per refueling outage and refueling of the entire core, the reactor could produce as much as 150 kilograms of plutonium (containing approximately 90 percent 239Pu) every 10 months.†
>
> ---
>
> † These data are obtained from the rough approximations of plutonium production in LWRs described earlier. Plutonium production rates vary broadly with fuel enrichment, and using lower fuel enrichments would likely reduce cost and optimize plutonium production. Significant additional analysis is required to determine more accurate estimates of fuel requirements and of material production and plutonium isotopic contents at these lower burn-ups.

China could devote one or a few of its civil LWRs to obtain one to a few hundred kg of FGPu/year, however this is unlikely to be China's first choice as it would involve operating reactors meant for electricity production inefficiently, and the plutonium is 90 percent Pu-240, not WGPu. To obtain 6 percent or less, Pu-240 would entail operation at a burnup closer to 3.5 MWt-d/kgHM, all but abandoning the use of the reactor for electricity production. As with recovering WGPu from CANDU spent fuel, the bottleneck here is the lack of spent fuel reprocessing capacity.

<u>Q14. Identify the normally civil spent fuel reprocessing plants, their capacity, and years of service. Are there any such facilities under construction?</u>

Since 1983, however, China has maintained a closed-fuel-cycle policy. In December 2010, it began testing a pilot civilian reprocessing plant with a capacity of 50 tons of spent fuel per year at the Jiuquan complex. Since then, however, the plant has been shut down most of the time because of technical problems. As of December 2015, according to China's declaration to the IAEA, it had separated 25.4 kilograms of plutonium. In early 2015, the government approved the construction of a 200 ton/year demonstration reprocessing plant at Jinta in Gansu province; CNNC started site preparation for the project that July (40º 19' 29.7" N; 98º 30' 53.3" E) and it is expected to be commissioned in 2025.[53] China recently began construction of another identical plant that is expected to come on line sometime before 2030.[54] CNNC also has been negotiating with France's Areva over the purchase of a commercial reprocessing plant with a capacity to reprocess 800 tons of spent fuel per year.[55]

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51. Michael May, Ed., "Verifying the Agreed Framework," LLNL, UCRIL-ID-142036 and CGSR-2001-001, April 2001, Chapter 5, available at https://cgsr.llnl.gov/content/assets/docs/CGSR-2001-001.pdf.
52. Ibid., p. 63.
53. For details see Zhang, Hui. "Pinpointing China's New Plutonium Reprocessing Plant," *Bulletin of the Atomic Scientists,* May 5, 2020, available at https://thebulletin.org/2020/05/pinpointing-chinas-new-plutonium-reprocessing-plant/.
54. Hui Zhang, See Hui Zhang, "China starts construction," available at http://fissilematerials.org/blog/2021/03/china_starts_construction.html.
55. Hui Zhang, "China's Fissile Material Production and Stockpile," IPFM p. 20, available at https://www.belfercenter.org/publication/chinas-fissile-material-production-and-stockpile.

Q15. Identify the nominally civil uranium enrichment facilities, their types, years of service and estimated capacity.

Typically, HEU for military and civil use are produced at the same facilities. As noted previously, HEU is not a pacing material for China's nuclear weapons production. China has three large operational gas centrifuge uranium enrichment plants (Lanzhou, Hanshong and Emeishan) with a combined capacity estimated to be on the order of 7.8 million SWU/year.[56]

The Lanzhou gas centrifuge enrichment complex (Plant 504) alongside the Yellow River near Lanzhou in Gansu province (36°08'53.30'' N; 103°31'24.49'' E) has an estimated capacity of 2.6 million SWU/year.[57]

The Hanzhong enrichment plant (official Chinese name: CNNC Shaanxi Uranium Enrichment Co., Ltd., or Plant 405) has an estimated capacity of 2.7 million SWU/year. It is located at (33°15'47.9" N/107°25'49.5" E), about 45 km NE of Hanzhong in Shaanxi province. It was built in three stages with the first two stages using Russian made centrifuges.

The Emeishan enrichment plant (Plant 814) has an estimated capacity of 2.45 million SWU/year. It consists of a pilot plant (0.25 million SWU/year) at (29°38'38.9 N/103°29'23" E) and a larger plant (2.2 million SWU/year) at (29°40'42 N/103°32'3.6" E), mid-way between Emeishan and Jiajiang, and about 5.75 km northeast of the pilot plant.

Two older gaseous diffusion uranium enrichment plants, at Lanzhau and Heping are now shut down.[58] HEU production in China began at Lanzhau on January 14, 1964.[59]

Besides the centrifuge facilities at Lanzhou, Hanzhong, and Emeishan, CNNC also plans to build two larger uranium-processing complexes in Hebei (referred to as "North Project") and Guangdong (referred to as "South Project").[60] China exports and imports low-enriched nuclear fuel, in effect exporting and importing the SWU needed to enrich the fuel.

56. Hui Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040," p. 2, available at http://npolicy.org/article_file/Hui_Zhang_Paper.pdf.
57. Ibid., p. 3 and Hui Zhang, "China's Fissile Material Production and Stockpile," IPFM, pp. 7-8, https://www.belfercenter.org/publication/chinas-fissile-material-production-and-stockpile.
58. Ibid., p. 6.
59. Ibid., p. 9.
60. Hui Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040, p. 8, available at http://npolicy.org/article_file/Hui_Zhang_Paper.pdf, cites CNNC stepped up deployment of nuclear fuel industrial park to help China 's nuclear power program go global. See *China Daily*, January 29, 2016, available at http://www.chinadaily.com.cn/interface/yidian/1120781/2016-01-29/cd_23312141.html.

Appendix

Technical Issues Related to Nuclear Weapons Production

A. Plutonium Production in Reactors

Plutonium-239 is produced in reactors through the absorption of neutrons in U-238 followed by two subsequent beta decays:

$$n + U^{238} \longrightarrow U^{239} \xrightarrow[24m]{\beta-} Np^{239} \xrightarrow[2.4d]{\beta^-} Pu^{239}$$

Production of plutonium in quantity requires copious supply of neutrons. This is achieved in a reactor, where a sustained and controlled chain reaction of fissioning U-235 nuclei provides a steady flux of neutrons to bombard U-238. The rate of production of plutonium depends on the design of the reactor and its fuel and the total energy production of the reactor, i.e., the operating power of the reactor integrated over time. If the reactor is designed to operate at a low power level, the neutron flux will be small and plutonium production will be low. Also, if the reactor is fueled with HEU, and there is no additional U-238 target material present, then the absence of U-238 in quantity results in very little plutonium production. This is the case with U.S. naval reactors fueled with 97.3 percent-enriched HEU.

In addition to Pu-239, heavier isotopes of plutonium, namely, Pu-240, Pu-241, and Pu-242 are also made by subsequent neutron absorption:

$$n + Pu^{239} \longrightarrow Pu^{240}$$

$$n + Pu^{240} \longrightarrow Pu^{241}$$

$$n + Pu^{241} \longrightarrow Pu^{242}$$

Also, Pu-238 is created by two sources: neutron capture by Np^{237} followed by beta decay of Np^{238}; and alpha decay of Cm^{242} which comes from the beta decay of Am^{242}, which in turn comes from neutron capture of Am^{241}.

The rate at which these competing reactions take place in the reactor, and the rate at which the various plutonium isotopes build up, are dependent on the design of the reactor and its fuel, and on the rate of energy production of the reactor. The plutonium is characterized by the percentage of Pu-240 it contains:

Grade of Plutonium	Percentage of Pu-240
Super-grade	2-3%
Weapon-grade (WGPu)	less than 7%
Fuel-grade (FGPu)	7% to less than 19%
Reactor-grade (RGPu)	19% or greater

For a given reactor type, it is useful to express the plutonium isotopic concentration as a function of the fuel exposure, or "fuel burnup." "**Fuel burnup**" can be measured as a percent of the fuel that is fissioned, but here it is more useful to express it as the thermal energy generated per unit of fresh fuel. In this case it can be expressed in units of megawatt-days of thermal power (MWt-d) per metric ton (t) of heavy metal (MWt-d/tHM) or per kilogram (kg) of heavy metal (MWt-d/kgHM). Heavy metal is the mass of the fuel, i.e., uranium and/or plutonium, in the fresh fuel, exclusive of the mass of the fuel cladding material.

a) Plutonium Production Reactors. Table 1A displays the plutonium production characteristics of the B-Reactor at Hanford in the United States (now shutdown), a typical graphite-moderated plutonium production reactor.

Table 1A. Plutonium production in grams (g) and the percent concentration of plutonium as a function of fuel exposure (mass % as a function of MWt-d/tHM) for the Hanford B reactor.

Fuel Burnup	**Pu Production**	**Isotopic Concentration (%)**			
MWt-d/tHM	**g Pu/MWt-d**	**Pu-239**	**Pu-240**	**Pu-241**	**Pu-242**
0	0.96	100	0.0	0.0	0.0
100	0.938	98.99	0.9985	0.01121	4.907×10^{-5}
200	0.917	98.00	1.955	0.04430	0.0003142
300	0.897	97.03	2.874	0.09309	0.001018
400	0.879	96.08	3.756	0.1593	0.002321
500	0.862	95.15	4.605	0.2398	0.004336
600	0.846	94.23	5.42	0.3329	0.007274
673	**0.835**	**93.57**	**6.00**	**0.4162**	**0.01012**
700	0.831	93.24	6.21	0.4373	0.01115
800	0.817	92.46	6.97	0.5517	0.01608
900	0.804	91.51	7.703	0.6748	0.02215
1,000	0.792	90.75	8.411	0.8057	0.02941

As can be seen from Table 1A, to ensure that the plutonium is weapon-grade, the average fuel burnup must be kept less than about 800 MWt-d/tHM. To prevent the buildup of Pu-240 beyond weapon-grade, the uranium fuel must be removed from the reactor early and often, typically after residing in the reactor for only a couple of months or so. Thus, reactors primarily for WGPu production are designed for rapid refueling and require a large amount of fuel to be "pushed" through the reactor.

From the second column of Table 1A, note that as the fuel burnup approaches zero the reactor produces about 0.96 g of Pu-239 per MWt-d of energy production. As the fuel burnup increases some of the plutonium is fissioned. At about 500-600 MWt-d/tHM, typical fuel burnups used for WGPu production in this type of reactor, the reactor produces about 0.85 g of WGPu per MWt-d of energy production.

Chapter 2

China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities

Hui Zhang

Since 2010, China has significantly expanded its indigenous enrichment capacity to meet the expected rapid increase of enrichment requirements.[61] Meanwhile, China has expanded its plutonium reprocessing and recycling capabilities for "saving uranium." The purpose of this report is to provide a better understanding of the development of China's uranium enrichment and plutonium recycling programs.

In part one, this report discusses the development status of China's uranium enrichment industry. Given China does not officially release information on its enrichment capacity, the report estimates China's current enrichment capacity based on satellite imagery, Chinese publications, and discussions with Chinese experts. Furthermore, the report makes projections of China's enrichment expansion over the next two decades.

In part two, this report reviews the development of China's reprocessing and fast reactors programs also referencing the latest reports and imagery. The report also projects cases for stocks of reactor-grade plutonium over next two decades. Finally, it estimates weapons-grade plutonium produced in the blankets of fast reactors.

Part One: China's Uranium Enrichment: Current State and Projected Expansion

Since the mid-2000s, China has adopted a strategy that combines domestic production, overseas exploitation, and purchases on the world marketplace in uranium in order to meet expectations of a rapid increase

61. By the end of 2019, China had 47 power reactors (45.5 GWe) in operation with 12 units under construction (12.2 GWe). China leads the world in new reactor construction. Developing nuclear power has become one key policy in reducing China's concerns about air pollution and climate change issues. In October 2012, after comprehensive post-Fukushima safety inspections of all plants in operation and under construction, China's State Council issued a new "Medium- and Long-Term Nuclear Power Development Plan (2011-2020)," calling for an installed capacity of 58 GWe by 2020, with another 30 GWe under construction by that time. In its 2016 issued 13th Five-Year Plan (2016-2020), China reaffirms the target called for in 2012. However, the target will be achieved by a few years delay. Nuclear energy will be a central element of meeting Chinese President Xi Jinping's 2014 commitment to produce 20 percent of Chinese primary energy from low-carbon sources by 2030. Many Chinese experts generally expect a capacity of about 110-150 GWe by 2030 to be feasible. Moreover, some authoritative studies recommend that China install a nuclear power capacity around 250-400 GWe by 2050. It is expected that China's nuclear expansion will see steady growth in the coming decades.

in uranium requirements. Known as the "Three One-Third" rule, one-third of its uranium comes from domestic supply, one-third from direct international trade, and another third from overseas mining by Chinese firms. Consequently, China has secured a huge amount of overseas uranium resources and more could easily be added, which would afford more than enough uranium to meet the requirements of China's most ambitious nuclear energy plan through 2050.[62]

While China will continue relying on domestic and overseas uranium resources, the China National Nuclear Corporation (CNNC)—the sole player responsible for enrichment services in China—has said that it maintains a policy of "self-sufficiency" in the supply of enriched uranium products needed to fuel its nuclear power plants.[63] In practice, to meet the expected rapid increase of enrichment requirements, CNNC has expanded its indigenous centrifuge enrichment capacity significantly since 2010. By 2020, China reached a total estimated enrichment capacity of about 7.8 million SWU (separative work units) (as shown in table 2.01) — enough to meet its reactors' demands of 7.5 million SWU annually. Moreover, China could have a surplus of up to 30 million SWU by 2029 as a result of a net import of SWU and the domestic overproduction since 2010, which means that China may not need to add new enrichment capacity at least until 2025. By 2040, the SWU requirement is expected to grow to about 18 to 32 million SWU/year.

How much will China build its enrichment capacities in the future? CNNC experts emphasize its policy of "meeting its domestic demand and targeting the international markets" in supply of enrichment services. They further address that China is able to produce enough enrichment uranium products to feed its domestic reactors and exported reactors.

China does not officially release information on its enrichment capacity. Based on satellite imagery, Chinese publications, and discussions with Chinese experts, this author made an estimate in 2015 on China's enrichment capacity.[64] Since then, there have been significant developments. On the one hand, new centrifuge facilities have been recently commissioned. On the other hand, enrichment expansion has been scaled back since 2016 due to China's slowed growth in nuclear power. Such trends could continue in the near future. However, China's SWU capacities are expected to expand significantly in the next two decades to align with the country's expected domestic and export reactor growth.

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62. Hui Zhang and Yunsheng Bai, *China's Access to Uranium Resources.* Mass.: Report for Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School, May 2015. http://belfercenter.ksg.harvard.edu/files/chinasaccesstouraniumresources.pdf.
63. Li Guanxing, "Status and Future of China's Front-end of Nuclear Fuel Cycle, *"China Nuclear Power* 3, (2010), in Chinese.
64. See more details in Hui Zhang, *China's Uranium Enrichment Capacity: Rapid Expansion to Meet Commercial Needs.* Cambridge, Mass.: Report for Project on Managing the Atom, Belfer Center for Science and International Affairs, Harvard Kennedy School, August 20, 2015. http://belfercenter.ksg.harvard.edu/files/chinasuraniumenrichmenntcapacity.pdf; also, Hui Zhang, "China's Uranium Enrichment Complex," *Science & Global Security*, 23:3, 171-190, 2015.

Table 2.01: China's Current Capacities (Million SWU/year)

Project	Capacity	Projects	Status
Lanzhou CEP 1	0.5	Russia-supplied phase III, Russian centrifuges	Operation in July 2001.
Lanzhou CEP 2	0.5	Called Plant 504 Project 2, Demonstration Project-1, domestic centrifuges	Operation in July 2010.
Lanzhou CEP 3	0.5	Called Plant 504 Project 3, Demonstration Project-2 Domestic centrifuges	Operation in December 2012.
Lanzhou CEP 4	1.1	Set up by Modular I (0.5 MSWU/year) and Modular II (0.6 MSWU/year)	Started construction in 2013. Modular 1 operational in 2015; Modular 2 operational in late 2016.
Lanzhou CEP 5	(1.4?)	Domestic centrifuges	In early 2015, pads for stack installation were under construction. It has been suspended since late 2015.
Lanzhou Plant 504 total operational	2.6	One Russian-supplied project, three domestic projects	The plant has more space ready for CEP expansion as needed.
Hanzhong CEP 1	0.2	Russian-supplied phase I, Russian centrifuges	Operation in February 1997. IAEA Safeguards.
Hanzhong CEP 2	0.3	Russian-supplied phase II, Russian centrifuges	Operation in January 1999. IAEA Safeguards.
Hanzhong CEP 3	0.5	Russian-supplied phase IV, Russian centrifuges	Normal operation in 2013.
Hanzhong CEP 4-I	1	North Expansion Centrifuge Project Phase I, Domestic centrifuges	Trials in 2013. Normal operation in March 2014
Hanzhong CEP 4-II	0.71	North Expansion Centrifuge Project Phase II, the first demonstration project with 2nd Gen domestic centrifuges.	Trials in 2017. Normal operation in 2018. The design capacity is about 0.7 million SWU/year. Later the centrifuge capacity is increased 1.5%.
Hanzhong CEP 5	(1.4?)	New District Project (nearby current site)	Initiated in 2015, operational before 2020 as planned. But no construction started, project significantly delayed.
Hanzhong Plant 405 total operational	2.71	Three Russian-supplied projects, two domestic projects	The plant first runs the 2nd Gen centrifuge machine. The plant has a new site for CEP expansion as needed.
Emeishan CEP 1 of plant 814	1.0	Domestic centrifuges	Project initiated in 2008. Operation around 2013.
Emeishan CEP 2 of plant 814	1.2	Domestic centrifuges	Earlier construction stage in 2014. At stage of installment and adjustment in 2015. Operational around 2017.

Emeishan CEP 3 of plant 814?	(1.4?)	Domestic centrifuges	A spare space nearby CEP1 was at early construction stage in Feb2015. But was suspended since 2016.
Heping GDP (plant 814)	(0.23)	Gaseous diffusion technology	Stopped HEU for weapons in 1987. Likely closed by 2019.
Emeishan pilot CEP of plant 814	0.25	Pilot CEP project, Domestic centrifuges	Operation in 2007. Likely non-weapons military or dual uses.
Plant 814 total operational	2.45	One pilot project and two larger CEP projects.	The plant has a spare space ready for CEP expansion as needed.

1. <u>Brief Development of China's Enrichment Industry and Technology</u>

China's uranium enrichment industry was initiated in the late 1950s to produce highly enriched uranium (HEU) for the nuclear weapons program. China produced HEU for weapons at two facilities: Lanzhou gaseous diffusion plant (GDP)(Plant 504) and Heping GDP (the Jinkouhe facility of Plant 814).[65] In January 1964, Lanzhou began to produce 90 percent HEU, which made China's first nuclear test possible in October 1964. It appears that Lanzhou stopped HEU production for weapons in 1980 and shifted to making low enriched uranium (LEU) for civilian power reactors and possibly for naval reactors. The plant was shut down on December 31, 2000 and has been replaced by centrifuge enrichment plants (CEP) since 2001.[66] The Lanzhou GDP was demolished in 2017. Over its lifetime, it produced an estimated 1.2 million SWU (MSWU) when it was producing HEU.

Heping GDP (Plant 814), a "Third Line" facility, began operating in 1970[67] and stopped its production of HEU for weapons in 1987. Since then, it is believed to have produced enriched uranium products for non-weapons military or dual-use purposes.[68] This plant was likely closed down in 2019. It is estimated that the Heping GDP produced 2.2 M SWU while it was producing HEU. It is estimated with both GDPs production of HEU, China could have a current inventory of about 14 ±3 tons of HEU available for weapons.

China decided in 1969 to build the Hanzhong plant (Plant 405) as a "Third Line" facility . In the mid-1980s, China constructed and operated a pilot centrifuge facility under project 405-1.[69] As China deepened its shift from military to civilian nuclear production in the late 1980s, the CNNC was eager to use what it hoped would be less-costly domestic centrifuge enrichment technology to replace its gaseous diffusion technology. It did not work well, however, and China decided in the early 1990s to import a Russian centrifuge facility to replace the project 405-1 as project 405-1A.

Under agreements in 1993, 1996, and 2008, China built Russian-supplied centrifuge facilities at Hanzhong and Lanzhou plants with four phases for a total capacity of 1.5 million SWU/year. As Russian centrifuge facilities were imported, CNNC started the localization process and designed its own centrifuges. It pro-

65. Hui Zhang, China's Fissile Material Production and Stockpile, IPFM Research Report No. 17, 2018 .Princeton, NJ: Princeton University, http://fissilematerials.org/library/rr17.pdf.
66. Jing Yongyu et al., Economic Analysis on Decommissioning of Lanzhou Gaseous Diffusion System, Proceedings of Workshop on Recycling Economics (in Chinese), 1 July 2008.
67. Wang Zhaofu, "60 Years of New China's Nuclear Energy Development Key Events," *China Nuclear Energy, 5*, (2009).
68. See, e.g., Cheng Lili, "Plant 814: The New Era of 'Small Yan'an" *Workers' Daily*, 26 March 2010, in Chinese.
69. See, e.g. Huang Wenhui and Qian Xikang, "Persons of Tsinghua University in Qinbashan*," China Youth Science and Technology* (in Chinese), No.12, 2003. http://wuxizazhi.cnki.net/Search/QNKJ200312016.html; also, Liang Guangfu, then-deputy chief engineer of plant 405, "To cast the light of the century by youth," talk at Tsinghua University, fall 2005.

duced its first centrifuge in 2002 and then began industrializing the process of centrifuge production.[70] This process was sped up after 2004 with China's "active development" of nuclear power. In August 2004, the government approved construction of an indigenous pilot centrifuge facility at Plant 814. It started operation in December 2007.[71]

In 2007, CNNC started to build a demonstration centrifuge facility at Lanzhou with a capacity of 0.5 million SWU /year. It was commissioned in 2010.[72] Since then, China has significantly increased its enrichment capacity at several sites, at Lanzhou, Hanzhong, and Plant 814 at Emeishan. CNNC also plans to build two larger uranium-processing complexes in Hebei and Guangdong. A new second-generation of centrifuge design was successfully deployed in a demonstration facility at the Hanzhong plant in 2017.[73]

2. Current State of Enrichment Capacities

CNNC is operating three large CEPs at Hanzhong (Shaanxi province, Plant 405), Lanzhou (Gansu province, Plant 504), and Emeishan (Sichuan province, the Emeishan civilian facility of Plant 814) to produce LEU for civilian purposes. Also, Plant 814 is operating a pilot CEP near Emeishan that is likely used for non-weapon military uses, or dual use.

Lanzhou Uranium Enrichment Plant

After the GDP was closed in December 2000, the Lanzhou plant launched its first centrifuge project (capacity of 0.5 million SWU/year) in July of 2001. Called Lanzhou Centrifuge Project 1 or the Enrichment Technical Renovation Project, the project is also sometimes referred to as Russian-supplied Phase III.[74] Since 2007, China has built three additional indigenous centrifuge projects at Lanzhou (see table 2.01).

After the construction of the pilot CEP at Emeishan Plant 814 in 2004, CNNC formally initiated in June 2007 Lanzhou Centrifuge Project 2 (Centrifuge Demonstration Project 1, officially, Lanzhou Centrifuge Commercial Demonstration Project) as an indigenous demonstration facility. In practice, the demonstration facilities were built based on a guidance of "one-time planning and step-by-step implementation," i.e. including Project 2 and Project 3.[75] Project 2 was commissioned in July 2010 and has an estimated enrichment capacity of about 0.5 million SWU/year. In early 2010, CNNC initiated Lanzhou Centrifuge Project 3 as a sister to Project 2. The facility was commissioned in December 2012. CNNC announced in June 2013 that it had successfully produced its first batch of enriched uranium using its own centrifuges. This commercial facility has an estimated capacity of around 0.5 million SWU/year.[76]

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70. Lei Zengguang, China has realized its independent uranium enrichment (in Chinese), May 17, 2013.
71. "The backbone of national defense: the story of Du Weihua, a national labor model and director of CNNC Plant 814," News of China Defense Industry, Postal and Telecommunications Workers' Union (in Chinese), May 25, 2010.
72. Based on communications with CNNC nuclear experts in July 2013. Also see: "China's Indigenous Centrifuge Enrichment Plant, *"Nuclear Intelligence Weekly*, October 25,2010. http://www.energycompass.com/pages/eig_article.aspx?DocId=691792.
73. CNNC, China's large-scale commercial demonstration project of a new generation of uranium enrichment centrifuge has passed the project completion acceptance, CNNC news, November 20,2020. http://www.cnnc.com.cn/cnnc/300555/300557/518709/index.html.
74. Wang, "60 Years of New China's Nuclear Energy Development Key Events."
75. CNNC, Lanzhou uranium Enrichment, China Nuclear Industry Daily, May 30, 2018.
76. Ibid.

In January 2013, China approved construction of Lanzhou Centrifuge Project 4.[77] Based on the experience of demonstration projects of Project 2 & 3, this larger commercial Project 4 was designed as a one-million SWUs-class production plant.[78] The first module (with an estimated enrichment capacity of about 0.5 million SWU/year) was commissioned in 2015. The second module (with an estimated enrichment capacity of about 0.6 million SWU/year) was commissioned in 2016.

Based on satellite images, construction of another main processing building (e.g. pads for stack installation, likely for Project 5) began in early 2015. However, construction appears to have been suspended in mid-2015. The pads recently showed weathering corrosion. It is not clear when the project will be completed. By March 2020, Lanzhou plant could have an estimated capacity of 2.6 million SWU/year.

Hanzhong Enrichment Plant

This plant has four centrifuge facilities, including three Russian-supplied centrifuge facilities built under Phases I, II, and IV of the bilateral agreements (with a total enrichment capacity of 1.0 MSWU/year) and a much larger indigenous centrifuge facility referred to officially as the North Expansion Centrifuge Project (Hanzhong 4). Currently, the Hanzhong plant has four CEP projects with a total enrichment capacity of around 2.71 million SWU/year.

After the Lanzhou demonstration centrifuge project (Lanzhou CEP 2) was commissioned successfully in 2010, Hanzhong started its own indigenous centrifuge project beyond those Russia had supplied. In January 2012, construction of the North Expansion Project began.[79] It includes two phases. Phase one was completed in 2013. It began operations around 2014.[80] Phase one has an estimated capacity of about 1 million SWU/year.[81] The first group of cascades of phase two, a large-scale commercial demonstration project with a new generation centrifuge, started to run in December 2017 and reached full operation in March 2018. [82] This project is the first to employ second-generation, indigenous centrifuges. The project passed national completion acceptance in November 2018. The overall technical level and economic efficiency of uranium enrichment have been further improved and reached the international advanced level.[83] It is estimated the Phase Two Project has an enrichment capacity of about 0.7 MWSU/year, a significant increase from an early module of about 0.5 MWSU/year. The second-generation centrifuge has been further improved by 1.5%. The Phase Two Project has an estimated enrichment capacity of 0.71 MSWU/year.

The Hanzhong plant is building another centrifuge facility, known as "The New District" Project. Construction began in 2015. It should be operational and is believed to have least one production line with two

77. China's National Nuclear Safety Administration (NNSA), "Annual Report 2013" (in Chinese).
78. CNNC, Lanzhou uranium Enrichment, op.cit. "Wei Jinhui, senior technician of uranium enrichment : keeps improving and dances with "nuclear," China's Gabsu webnews, April 23, 2015. http://gs.sina.cn/news/2018-04-23/detail-ifzqvvrz6734421.d.html.
79. NNSA, "Annual Report 2012."
80. NNSA, "Annual Report 2014."
81. As the Lanzhou centrifuge project 4, a commercial centrifuge facility of a class of 1 MSWU/year production line generally consists of two modules (assuming 0.5 MSWU/year for a pre-2015 module and 0.6 MSWU/year for a post-2015 module. But the post-2017 module could be about 0.7 MSWU/year with 2ed Gen centrifuge).
82. CNNC, China's large-scale commercial demonstration project of a new generation of uranium enrichment centrifuge has passed the project completion acceptance, op.cit; Liu Caiyu , New uranium enrichment centrifuges go commercial, , Global Times, November 20,2018, http://www.globaltimes.cn/content/1128247.shtml.
83. CNNC, China's large-scale commercial demonstration project of a new generation of uranium enrichment centrifuge has passed the project completion acceptance, op.cit.

modules of GEN II centrifuges (about 1.4 MSWU/year). However, this New District Project has not made significant progress since 2016. As with other projects at Lanzhou plant and Plant 814, further work on it seems to have been suspended. These delayed or suspended projects may be waiting for the 14^{th} Five Year Plan (2021-2025) which will be issued in 2021.

In sum, the Hanzhong plant currently has a total of an estimated capacity of 2.71 million SWU/year in operation, and of the New District Project about 1.4 MSWU/year or more.

Emeishan Enrichment Facilities of Plant 814

Plant 804 hosts enrichment facilities at three sites in Sichuan province. The Heping GDP at Jinkouhe of Leshan City started operation in 1970 and likely closed in 2019. Plant 814 is operating a pilot CEP near Emeishan City. The larger commercial centrifuge plant (Emeishan CEP 1 and 2) of Plant 814 is located about 3.6 miles away from the pilot facility at the town of Shuangfu near Emeishan city.

The Emeishan CEP 1 Project (referred to as Plant 814 centrifuge Project 1) was initiated in 2008.[84] It started construction around 2011. Based on satellite images, this facility may have gone into operation around 2013. New information related to the Lanzhou Project 4 suggests that this facility has a capacity of around 1 million SWU/year.[85] Based on satellite images, Emeishan CEP 2 was at the early construction stage in 2014. In 2015 and 2016, it was likely at the stage of installment and adjustment. This facility could have been commissioned around 2017. Emeishan CEP 2 is assumed to have a capacity around 1.2 million SWU/year.[86]

Satellite images show that the space alongside CEP 1 is perhaps ready for an additional CEP (Emeishan CEP 3). The satellite image in February 2015 shows some early construction activities including preparation for pad construction. But subsequent satellite images also show that construction has been suspended since at least February 2016.

Plant 814 also operates a pilot CEP near Emeishan city. This pilot facility started construction in 2004 and was commissioned in 2007.[87] It could have an estimated enrichment capacity of 0.25 million SWU per year.[88] Given that the site is isolated from the public transportation system and has a dedicated road and secured entrance, it is most likely a facility to produce enriched uranium products for non-weapons military uses or dual use, including production of low-enriched uranium for naval reactors and highly enriched uranium for research reactors.

84. Development and Reform Bureau of Emeishan city, Key Work Points in 2008, March 18, 2008.
85. The total footage of the presumed enrichment building is comparable to that of Lanzhou project-4. The Emeishan CEP1 could host two pre-2015 modules (i.e. each of 0.5 MSWU/year) .
86. Given it was operational later than that of the second module of Lanzhou centrifuge project 4 but earlier than that of the first use of the 2^{nd} Gen centrifuge in Hanzhong plant, the Emeishan CEP2 is likely using two modules with each of 0.6 MSWU/year.
87. “The backbone of national defense: the story of Du Weihua, a national labor model and director of CNNC Plant 814,” op.cit.
88. The size of the roof is half that of Lanzhou Centrifuge Project 3 (0.5 million SWU/year), therefore it is estimated that the facility could have an enrichment capacity of 0.25 million SWU/year.

The Two Uranium-processing Complexes

Besides the centrifuge facilities at Lanzhou, Hanzhong, and Emeishan, CNNC also plans to build two larger uranium-processing complexes in Hebei (referred to as "North Project") and Guangdong (referred to as "South Project").[89] Aiming to support China's nuclear power "going global" strategy, CNNC wants to build each of these complexes as a "one-stop" service center that will include uranium purification and conversion, uranium enrichment, and fuel fabrication plants. [90]

Until 2013, CNNC had a plan to build such a center in Heshan of Jiangmen in Guangdong province. It was reported the enrichment capacity was about 7 million SWU/year.[91] However, the Heshan project was cancelled in July 2013 after large-scale protests against the project.[92] In 2014, CNNC relocated the Heshan-type project (on a similar scale) at the Cangdong Economic Development Zone near Cangzhou City in Hebei Province. This uranium-processing complex (the "North Project") is solely owned by CNNC and will cost around 40 billion yuan (~$6 billion). CNNC plans to have a partial production capacity by 2018 and will have full capacity after 2020.[93] The site preparation started in 2015.[94] Based on satellite images of the site, early construction of a fence and a few auxiliary buildings began in April 2017. However, there has been no significant construction activities at the site since then. The project may be suspended or significantly delayed as other CEP projects mentioned above.

Also, CNNC and China General Nuclear Power Corporation (CGN) have worked on a joint venture of a uranium-processing complex (the "South Project") to be located at Guangdong province. It would be similar to the North Project in terms of production capacity and financial investment.[95] CNNC officials mentioned in March 2016, the "South Project" was looking for a site then. [96] However, since then, this project has also seemingly been suspended.

3. Projected Enrichment Expansion in China between 2020 and 2040

China's future expansion of enrichment will depend on a number of factors: the number of domestic reactors to be installed, how many reactors China expects to export, and the share of international markets China plans. CNNC already is able to produce enough enrichment uranium products to feed its domestic reactors and exported reactors.

89. CNNC stepped up deployment of nuclear fuel industrial park to help China 's nuclear power "go global," January 29, 2016, China Daily. http://www.chinadaily.com.cn/interface/yidian/1120781/2016-01-29/cd_23312141.html.
90. Lin Chunting, "Coordinated with nuclear going out, CNNC plans to set up international nuclear fuel supply centers for 80 billion RMB," News, yicai.com (in Chinese), March 3, 2016. http://m.yicai.com/news/4757072.html.
91. WNA, "China's Nuclear Fuel Cycle." http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx. Also, this enrichment capacity is consistent with other Chinese experts' estimates on uranium conversion capacity for the uranium-processing complex.
92. Liu Qingshan, "Waiting to Know the East Wind: Heshan Setback," China SOE, No. 4, (2014), pp. 28–29. Based on an interview with CNNC president Sun Qin. The China SOE (State Owned Enterprise) is run by the State Own Assets Supervision and Administration Commission of the State Council.
93. "Announcement on Environmental Impact Assessment of CNNC's Nuclear Fuel Industrial Park Construction Project," November 13, 2014. Cangzhou Government, http://www.cangzhou.gov.cn/zwbz/zwdt/gggq/301500.shtml.
94. "Speeding up Nuclear Industrial Layout in Hebei," China Energy News (in Chinese), March 23, 2015.
95. CNNC restarts Guangdong Nuclear Fuel Industry Park project, Yicai web news, July 20,2015, https://www.yicai.com/news/4647348.html.
96. Lin Chunting, "Coordinated with nuclear going out, CNNC plans to set up international nuclear fuel supply centers for 80 billion RMB," op.cit.

3.1 China's Domestic Reactor Requirements

Any estimate of China's future uranium enrichment demands depends upon accurate projections of the number and size and type of China's nuclear power facilities. The government is working on the 14th Five Year Plan of nuclear power development and expect it to be issued in early 2021, which would reveal the new official target of nuclear power development in the coming decade.

Recently, Chinese nuclear experts and related thinktanks have made various projections of China's nuclear reactor capacity over the next two decades. For instance, in 2018, Xu Yuming, Deputy Director of Expert Committee of China Nuclear Energy Industry Association (CNEA), projected about 100-120 GWe would be installed by 2030 and 150GWe by 2040.[97] In 2019, China Nuclear Power Development Center (or NDRC) and State Grid Energy Research Institute issued their joint report of "Study on China's Nuclear Power Development Planning". This report forecasts China will reach 131GWe (accounting 10.0% of total electricity generation) by 2030, 169 GWe (accounting 13.5 % of total electricity generation) by 2035, and 335 GWe (accounting 22.1 % of total electricity generation) by 2050.[98] In January 2020, the CNNC nuclear energy experts suggested that China should have an installed capacity of 70 GWe with another 36 GWe under construction by 2025, and an installed capacity of 150 GWe with another 50 GWe under construction by 2035. [99]

Table 2.02 shows three scenarios (high, medium, and low) for China's nuclear power capacity through 2040. These scenarios are based on Chinese publications and recent communication with Chinese energy and nuclear experts. Under a high-growth scenario, China's nuclear-generating capacity would go from about 50 GWe in 2020 to about 225 GWe by 2040.[100] This high-growth scenario would constitute the most optimistic projection. It could be taken as a bounding case. For the low-growth scenario, China's nuclear fleet would have a total installed capacity of 130 GWe by 2040.[101] However, some Chinese nuclear experts argue even this so-called low-growth scenario could still represent an optimistic projection. Under a medium-growth scenario, China's nuclear fleet would go from a total installed capacity of 50.3 GWe in 2020 to 62.5 GWe by 2025; 110 GWe by 2030; and 180 GWe by 2030.[102]

97. Wang lu, "China's nuclear power development is still in a period of important strategic opportunities," Economic information Daily, January 31, 2018. http://dz.jjckb.cn/www/pages/webpage2009/html/2018-01/31/content_40574.htm.
98. China Nuclear Power Development Center and State Grid Energy Research Institute, "Study on China's Nuclear Power Development Planning", China atomic energy press, July 2019.
99. Yunshen Bai, "Recommendations on nuclear power of "14th Five-Year Plan" and the mid-and long-term development plan," Power Decision and Public Opinion Reference, No.1 &2, January 3,2020.
100. According to the "Study on China's Nuclear Power Development Planning" (op.cit), China will install about 170 GWe and 335 GWe by 2035 and 2050, respectively. Here assumes it is increased linearly from 2035 to 2050. Thus, 225 MWe will be installed by 2040.
101. Assuming about 170 MWe installed by 2050 (accounting around 11 % of total electricity generation, i.e. about half of that of high growth scenario (335 MWe). Here assumes it is increased linearly from 2035 to 2050. Thus, 130 MWe will be installed by 2040.
102. Based on current practice of operating and under construction power reactors by March 2020, it is estimated about 62.5 MWe would be installed by 2025. Then it is assumed under the base-growth scenario, nuclear reactor capacity targets are taken the average of the high- and Low-growth scenarios from 2030 to 2040.

Table 2.02: Projections for China's Nuclear Capacity Targets through 2040

Cases	2020	2025	2030	2035	2040
High	50.3	70	130	170	225
Medium	50.3	62.5	110	140	180
Low	50.3	60	90	110	130

To estimate the SWU requirements for China's projected nuclear power development, it is assumed that PWR using a once-through fuel cycle will be the mainstay technology choice at least through 2040.[103] It is also assumed the annual SWU requirement per GWe PWR would be about 130 metric ton-SWU.[104] Then, based on China's nuclear power forecast as shown in table 2.01, the projections of China's SWU requirements of its domestic power reactors through 2040 are shown in figure 2.01. Therefore, for a base case, we can estimate that the annual SWU requirement will increase from around 7.5 million SWU in 2020 to around 17 million SWU/year by 2030 and around 24 million SWU/year by 2040.[105]

Besides Chinese domestic reactors requirements, China will need more SWU capacities if it is to supply SWU for a substantial number of Chinese exported reactors and account for a significant share of the international market. China has made "going global" an important strategy to promote its new economic growth mode. The government actively supports advanced nuclear technology as one of China's new high-tech exports. China hopes its nuclear export efforts can be facilitated through its "One Belt, One Road" initiative proposed by president Xi Jinping in 2013 which aims to promote China's economic development through global economic integration and trade. Chinese officials and experts expect there will be over 40 nations along the "one belt, one road" area to develop nuclear power. If China can take a share of 20-30% of the expected nuclear market, China would export about 30 reactors—tremendous business opportunities. [106] As shown in figure 2.01, a projection of SWU requirements for exported reactors through 2040 is given.[107] It can be expected China's "going global" strategy will speed up in the coming decade. As China actively pursues this policy, it is expected China will gradually increase its SWU share of the international market.

103. Given the current dominance of PWR designs, we assume that in practice these reactors will account for the majority of China's nuclear growth; the exceptions are the two Candu reactors (2 x 728 MWe) and two CFR-600 fast reactors planned to be operational in 2020s.
104. Zhang, China's Uranium Enrichment Capacity: Rapid Expansion to Meet Commercial Needs, op.cit. In addition, we assume that producing the initial core for each new reactor will require the equivalent of about three times the annual SWU requirement.
105. To estimate SWU demand in 2020, it is assumed a total nuclear capacity of around 50.3 GWe in 2020 by adding 4.6 GWe PWRs of new capacity to the total of 45.7 GWe in 2019, as we should include SWU for the new cores. In addition, the total nuclear capacity of 50.3 GWe needs to subtract about 1.5 GWe of the two Candu reactors (which do not need SWU).
106. Lin Chunting, "Coordinated with nuclear going out, CNNC plans to set up international nuclear fuel supply centers for 80 billion RMB," op.cit.
107. Here is assuming a total of 30 Hualong One PWRs (about 1.2GWe each) are exported by 2040: 2 operational by 2025 in Pakisain, 10 operational by 2030, then increased linearly to 30 operational by 2040.

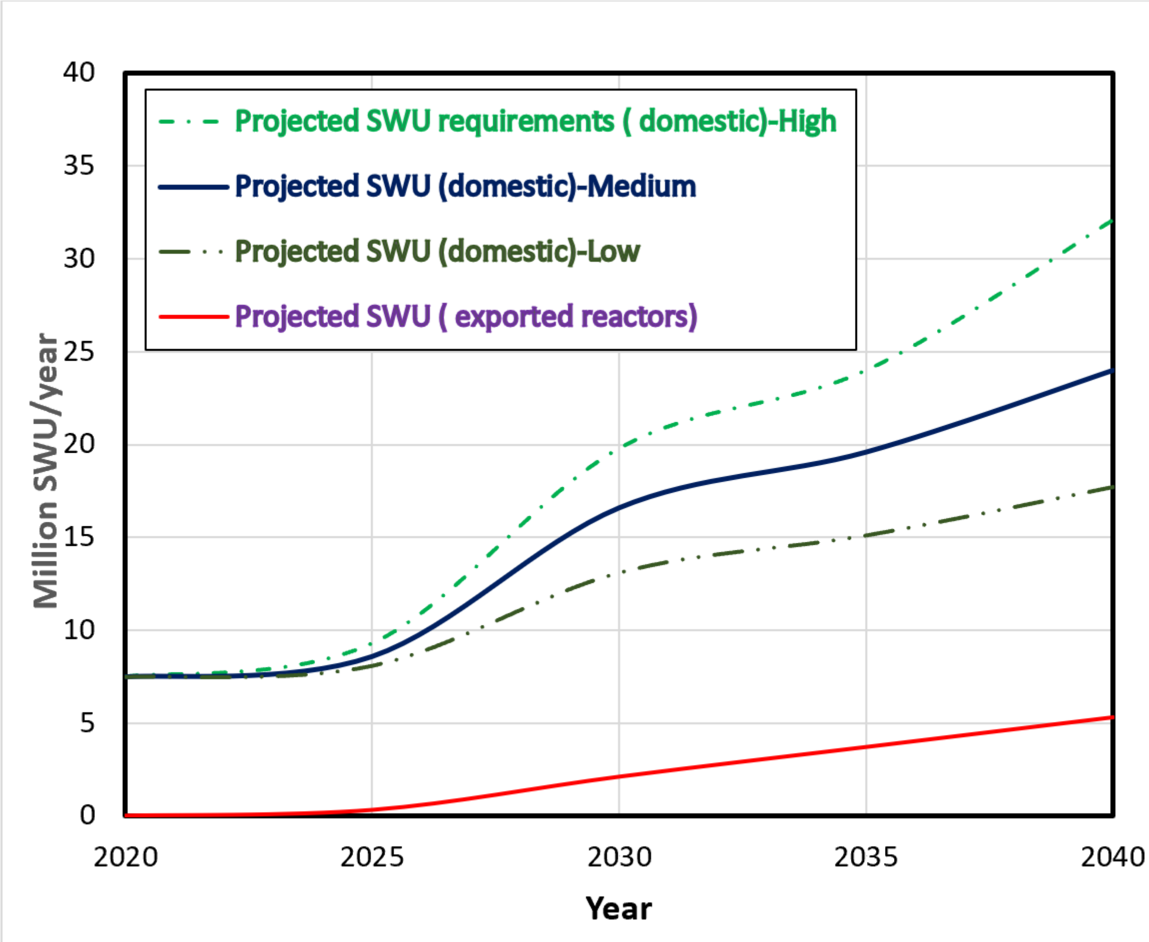

Figure 2.01: Projections of China's SWU requirements for domestic and exported reactors through 2020 to 2040

3.2 Imports and Exports of SWU in the Past

Over the past decade China has imported a significant amount of SWUs (in the form of EUP). In particular, when China purchases foreign reactors, it often requires the foreign vendors to supply the first few loads of enriched fuel. These deals save China more SWU. The following commitments are examples of such requirements. Framatom supplies fresh fuels including two first cores and 17 reloads for its two exported EPRs at the Guangdong Taishan nuclear power plant.[108] Under a 2008 agreement, Tenex of Russia supplies 6 million SWU as LEU products from 2010 to 2021 for those four AP1000 reactors sold by Westinghouse.[109] Urenco supplies 30% of the enriched uranium for the two Daya Bay reactors in Guangdong; and Russia's TVEL will supply the fuel for Tianwan 3 and 4 (two VVERs) until 2025.[110]

108. WNA, "China's Nuclear Fuel Cycle (Updated October 2019)." https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx.
109. Ibid.
110. Ibid.

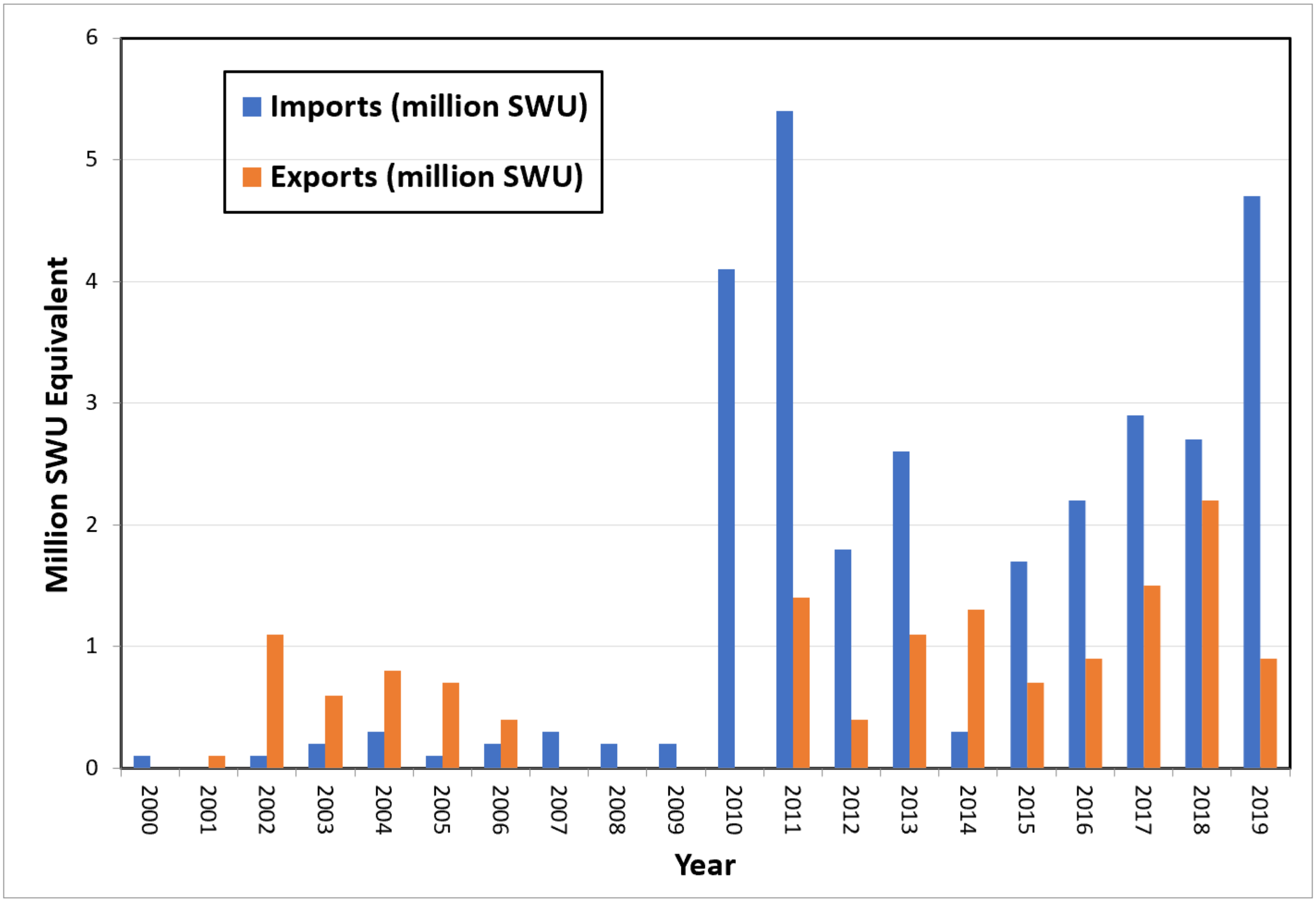

Figure 2.02: China SWU Imports, 2000-2019. Assumes Product @4.95 w/o, Tails@0.25w/o. Credit: UxC, LLC.

As a result, as shown in figure 2.02, China imported about 28.4 million SWU from 2010 to 2019, while some of these imports are material exported by China for processing into fuel assemblies for use in Chinese reactors.[111] Meanwhile, based on the UxC data, China exported to international utility customers about 10.4 million SWU from 2010 to 2019. In addition, as shown in figure 2.03, China produced around 50 million SWU from 2010 to 2019. The domestic SWU requirement was around 39 million SWU during the same period. Finally, combining those imported and exported SWU, China could have a surplus of up to 30 million SWU by 2019.[112] This means that China may not need to add new enrichment capac-

111. See, "China's Impact on the Global Enrichment market," UxC Market Outlook, Q2, 2018, UXC.com.
112. The net imported SWU (i.e. the total imports minus the total exports) from 2010 to 2019 was about 18 million SWU. Considering the surplus of domestic production (i.e. the domestic productions minus the domestic needs) during the same period was about 11 million SWUs, thus China could have a surplus of 29 million SWU by 2019. However, it should be noted that part of it could be used for non-civilian sector. For example, the Heping GDP and the pilot CEP of Plant 814 could produce about 4.6 million SWU from 2010 to 2019. Both facilities are believed to be dual uses. Given it is not clear how much SWU was used for non-civilian sector in the past decade, the estimated surplus of 29 million SWU would be the maxi-

ity at least until 2025. This could also show that, since 2016, China has been slowing down to add new enrichment capacity.

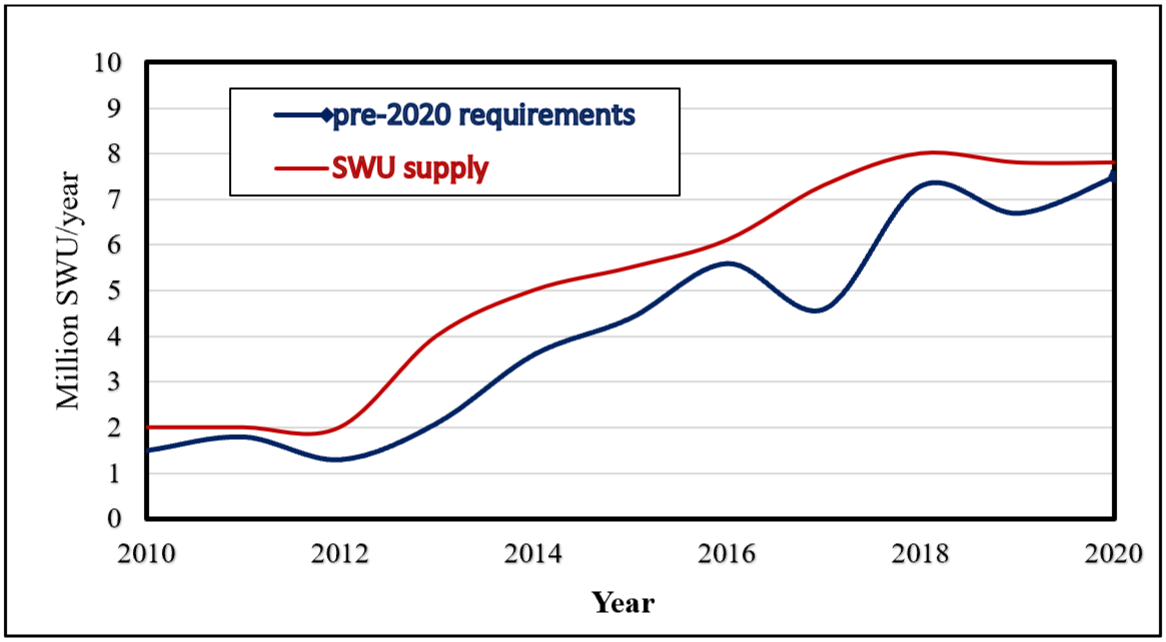

Figure 2.03: China's SWU requirement and supply (2010-2020)

3.3 Projections of China's Enrichment Supply Capacities 2020-2040

Based on the past decade, as shown in figure 2.03, China's domestic SWU supply has aligned well with its reactors' requirement. It is assumed China's future SWU supply would mainly follow this trend from 2020 to 2040. The following assumptions are for three scenarios. As a high case, the supply should meet its domestic reactor requirement for the high-growth scenario and those exported reactors' requirement as shown in figure 2.01. As a medium case, the supply would meet its domestic reactor requirement for the medium scenario as shown in figure 2.01. It is also assumed the net SWU imports or exports would be insignificant compared to the main requirement from domestic reactors. As a low case, the SWU supply should meet its domestic reactor requirement for the low scenario as shown in figure 2.01. Moreover, it is assumed there is a net SWU import around 1.5 million SWU/year, and there are no significant exports of reactors. In practice, as China's General Nuclear Power Corporation (CGN) is pursuing to import more enriched products, the net import could be higher. Recently a joint venture between Kazakhstan's Kazatomprom and CGN has built a fuel fabrication plant with a capacity of 200 tons/year in eastern Kazakhstan. It's first shipments to China are expected in 2021.[113]

Consequently, the projections in figure 2.04 show China may have a total capacity of about 12-22 million SWU/year by 2030, and 16-37 million SWU/year by 2040.

mum amount available for the future civilian uses.

113. Mattia Baldoni, Kamen Kraev, Kazatomprom-CGN Joint Venture To Supply Framatome Assemblies To China, 5 March 2020, https://www.nucnet.org/news/kazatomprom-cgn-joint-venture-to-supply-framatome-assemblies-to-china-3-4-2020.

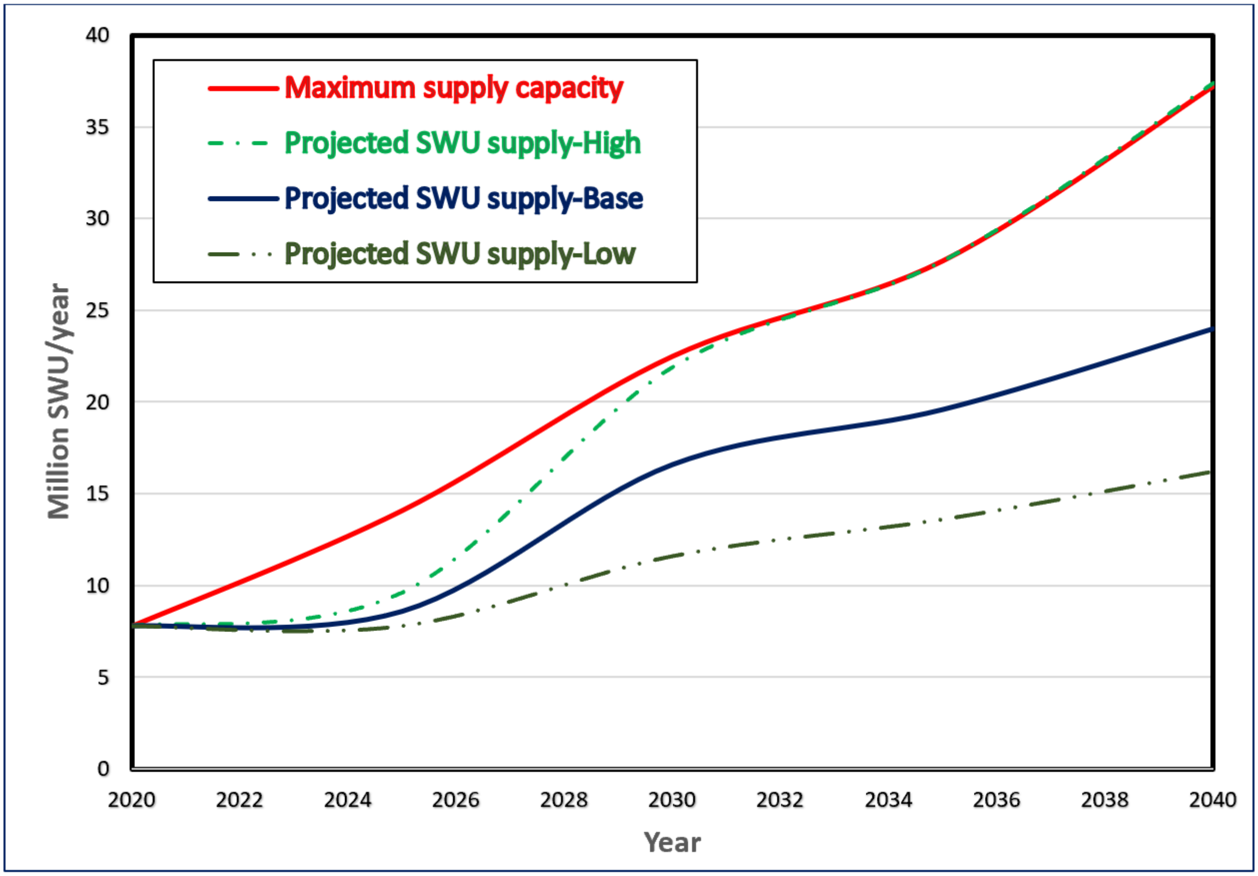

Figure 2.04: Projected China's SWU supply (2020-2040)

Can China meet the projected supply capacity in the coming two decades? Based on CNNC's plans, domestic centrifuge technology, centrifuge production capacity, and space availability at each site, the maximum capacity is assumed as follows: China has the ability to add about 1-1.5 MSWU of additional capacity annually (with the second generation centrifuge machines). Besides CNNC's current operational capacity of 7.8 million SWU/year, those projects under construction or delayed, like the Lanzhou CEP5 (1.4 million SWU/year), New District Project of Plant 405 (1.4 million SWU /year) and half of the North Project of Cangzhou uranium-processing complex (3.5 million SWU/year) are commissioned to be built by 2025. Taking the Emeishan CEP3 of Plant 814 (1.4 million SWU/year) into account, the entire North Project of Cangzhou complex (7 million SWU/year), and half of the South Project of Guangdong uranium complex (3.5 million SWU/year) are commissioned to be built by 2030. The entire South Project of Guangdong uranium complex (7 million SWU/year) and new CEP facilities with another 3.5 million SWU/year are commissioned to be built by 2035; adding another 7.5 million SWU/year by 2040.

As shown in figure 2.04, China's maximum SWU supply capacity can meet the projected amount even for the high case. China's SWU supply would likely align with its reactors' requirement as it has done for the past decade. However, if China decided to build its enrichment capacity according to the maximum supply line as assumed here, and China's need is as the medium case shows in figure 2.04, the cumulative domestic SWU supply would total about 450 million SWU over the period between 2020 and 2040. The cumulative SWU requirement through the same period would be about 300 million SWU. This indicates that China could have a total surplus of around 150 million SWU through 2040, which could then be sold on the international market.[114] However, China would face huge challenges to make such a case happen, including making its enrichment services more economically competitive to other players. China could produce more SWU as an important hedge against future potential uranium shortfalls. China could also build more SWU capacities than it really needs so that they can use it for underfeeding and/or tails re-enrichment in the future if they don't have sufficient natural uranium supply. However, the fact that China has recently been slowing or stopping its enrichment construction may show China could have no wish to build much more than it needs.

3.4 A Discussion on China's HEU Production Capacities

In the 1980s, when both the U.S. and Soviet Union had peaked their nuclear arsenals, China stopped HEU and plutonium production for weapons even without requirements from international agreements.[115] China's use of HEU for non-weapons purpose is expected to be very limited. Its new generation of naval reactors is likely to continue to use LEU fuel and future HEU use in its research reactors will not be significant. China has not released any information about its non-weapons HEU stock but could have produced a large stock to meet its needs since it ended HEU production for weapons back in 1987. The Heping GDP and the pilot CEP of Plant 814, both assumed to be dual use, could each produce more than 1 ton of 90 percent enriched HEU per year.

To estimate China's HEU production capacity, all the civilian SWU capacity for LEU production can be used to make HEU for weapons, but it is unlikely in practice. One million SWU is sufficient to produce about 4.8 tons of weapon-grade HEU,[116] about 240 implosion bombs (assuming 20 kg of 90% HEU for each bomb). Thus, a total of 7.8 million SWU/year, what China currently could produce would result in about 37.4 tons of WgHEU each year (about 1870 bombs/year). This is about 2.7 times China's current inventory of about 14 tons of HEU for weapons. As a projection of China's enrichment capacity as the medium case shown in figure 2.04, China could have an enrichment capacity of 16.6 million SWU/year by 2030 and 24 million SWU/year by 2040, respectively, which is equal to producing about 80 tons of weapon-grade HEU per year by 2030 and about 115 tons/year by 2040. The cumulative domestic SWU supply would total about 300 million SWU over the period between 2020 and 2040, sufficient to producing about 1440 tons of weapon-grade HEU (about 72,000 bombs). However, it is impossible for China to shut down its all power reactors and produce such a HEU stock even much more than that of the total of U.S. and Russian stockpiles.[117]

It also should be noted that some of China's CEPs are under IAEA safeguards. Under its Voluntary Offer Safeguards agreement, China once offered those three Russian-supplied facilities as phase I & II at Hanzhong plant and phase III at Lanzhou plant for selection for IAEA safeguards. Due to its shortage of funds, the IAEA picked only the Hanzhong facilities.[118] The two Russian-supplied centrifuge facilities as phase I and phase II were placed under IAEA safeguards as part of a Tripartite Safeguards Agreement be-

114. This scenario assumes China would build its enrichment capacity according to the maximum supply line as shown in figure 4, but China's needs were as the medium case as shown in figure 4. Such a scenario would result a huge surplus of SWU. In practice, based on past experience as shown in figure 3, China's SWU supply would likely align with its reactors' requirement.

115. Hui Zhang, "The history of fissile-material production in China," The Nonproliferation Review, 25:5-6, 2018, 477-499.

116. Producing one kilogram of HEU product enriched to 90% will require 208.3 kg-SWU with natural uranium feed for tails at 0.25 percent.

117. It is estimated by 2016 the United States and Russia have a HEU stock of 574.5 tons and 679 tons, respectively. http://fissilematerials.org/countries/.

118. Communications with CNNC nuclear experts, October 2014.

tween the IAEA, Russia's Minatom, and China's Atomic Energy Authority (CAEA).[119] The fact that China offered IAEA inspectors access to Hanzhong and Lanzhou plants may indicate they are both dedicated to pure civilian purposes.

Given the Plant 814 is not open like Lanzhou and Hanzhong are, if China ever resumes HEU production for weapons, it could use part of or full enrichment capacity of Plant 814. The pilot CEP of Plant 814 (0.25 million SWU/year) is sufficient to produce about 1.2 tons of weapon-grade HEU/year. The CEP1 of Plant 814 (1 million SWU/year) is sufficient to produce about 4.8 tons of weapon-grade HEU/year. The CEP2 of Plant 814 (1.2 million SWU/year) is sufficient to produce about 5.8 tons of weapon-grade HEU/year. As a low case, assuming China uses the pilot CEP to produce about 1.2 tons each year, it could produce about 12 tons of HEU by 2030 and 24 tons of HEU by 2040, about 1.7 times China's current stock. As a medium case, assuming China uses the pilot CEP and CEP1 of Plant 814 to produce a total about 6 tons of HEU each year, it could produce about 60 tons of HEU by 2030 and 120 tons of HEU by 2040, about 8.6 times China's current stock. As a high case, assuming China uses the pilot CEP, CEP1, and CEP2 of Plant 814 to produce a total about 11.8 tons of HEU each year, it could produce about 118 tons of HEU by 2030 and 236 tons of HEU by 2040, about 17 times China's current stock.

However, while China has the technological capacity and economic resources to produce more HEU for weapons, such a production would be essentially constrained by its long-standing nuclear policy that features a no-first-use pledge, a "lean and effective" nuclear force, and the strive to avoid a costly nuclear arms race.

Part Two: China's Plutonium Recycling: Current Practices and Projected Capacities

Since 1983, China has had the objective of developing plutonium breeder reactors with plutonium recycling. According to its proponents, the major benefits of this policy would be full utilization of the energy in China's uranium resources, a drastic reduction in the required volume for radioactive waste in a deep underground repository, and a path forward for the spent fuel accumulating in China's reactor pools.[120]

Since 2004, when China shifted its nuclear power development policy from "moderate development" to "active development," China has been developing its plutonium recycling strategy through three stages: pilot, demonstration, and commercial facilities. In 2010, China began the first stage by testing a pilot civilian reprocessing plant and running an experimental fast reactor. Even though those pilot facilities did not perform well, in 2015, China moved forward to the next second stage including a demonstration reprocessing plant, a MOX facility, and two demonstration liquid-sodium-cooled fast-neutron reactors. Meanwhile, CNNC pushed toward the third stage by negotiating with France's nuclear fuel-cycle company Orano (formerly Areva) over the purchase of a large commercial reprocessing plant, and has proposed construction of large commercial fast-neutron reactors for 2028.

This report will assess those plutonium recycling programs and estimate the plutonium production and the stockpile of cumulative unused plutonium over the next two decades.

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119. A. Panasyuk, A. Vlasov, S. Koshelev, T. Shea, D. Perricos, D. Yang, and S. Chen, "Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped with Russian Centrifuges," IAEA-SM-367/8/02 (IAEA, 2001).
120. Xu Mi, "Fast Reactor Development for a Sustainable Nuclear Energy Supply in China" (presentation, Harvard-Tsinghua Workshop on Nuclear Energy and Nuclear Security, Beijing, China, March 14-15, 2010); Gu Zhongmao, "The Sustainable Nuclear Energy Needs Closed Fuel Cycle" (presentation, Harvard-Peking University Workshop on the Economics of Nuclear Reprocessing, Beijing, China, October 15, 2011).

1. China's Reprocessing Programs: Current Practices and Outlooks

A Brief History of China's Military Reprocessing Facilities

China produced plutonium for weapons at two nuclear complexes, Jiuquan (Plant 404) and Guangyuan (Plant 821), both closed in 1987. China has a military plutonium stock: 2.9 ± 0.6 tons (2.3-3.5 tons) for weapons.[121]

China began to develop its military reprocessing program in 1956. In 1962, Beijing decided to first build an intermediate-scale pilot plant (also referred to as the Small Plant, or the first project) and then build a large military reprocessing plant later (also referred as the Large Plant, or the second project). China built both projects at the Jiuquan nuclear complex (Plant 404) (see figure 2.05).

The intermediate pilot reprocessing plant started construction in 1965 and began operation in September 1968. The plant had two production lines that could together process 0.4 tons of spent fuel per day and operated over 250 days a year.[122] It separated the plutonium for China's first test of a plutonium-based weapon in December 1968. The pilot reprocessing plant stopped plutonium separation when a larger plant, also built near the reactor site, began operating in April 1970. The large plant stopped plutonium separation around 1987. In 1969, Beijing decided to build a second military plutonium reprocessing plant (Plant 821) at Guangyuan, Sichuan province as a "third line" project. That plant started operation in 1976 and closed around 1987.[123]

China's military reprocessing program helped lay a foundation for China's civilian back-end fuel cycle program and Jiuquan Plant 404 was selected as a base for civilian reprocessing activities. The civilian pilot plant is located at the same site.

121. Zhang, China's Fissile Material Production and Stockpile, IPFM Research Report No. 17, 2018 . op.cit.
122. Li Jue, Lei Rongtian, Li Yi and Li Yingxiang, eds., China Today: Nuclear Industry, China Social Science Press, Beijing, 1987 (in Chinese), p.227.
123. Zhang, China's Fissile Material Production and Stockpile, IPFM Research Report No. 17, 2018 . op.cit.

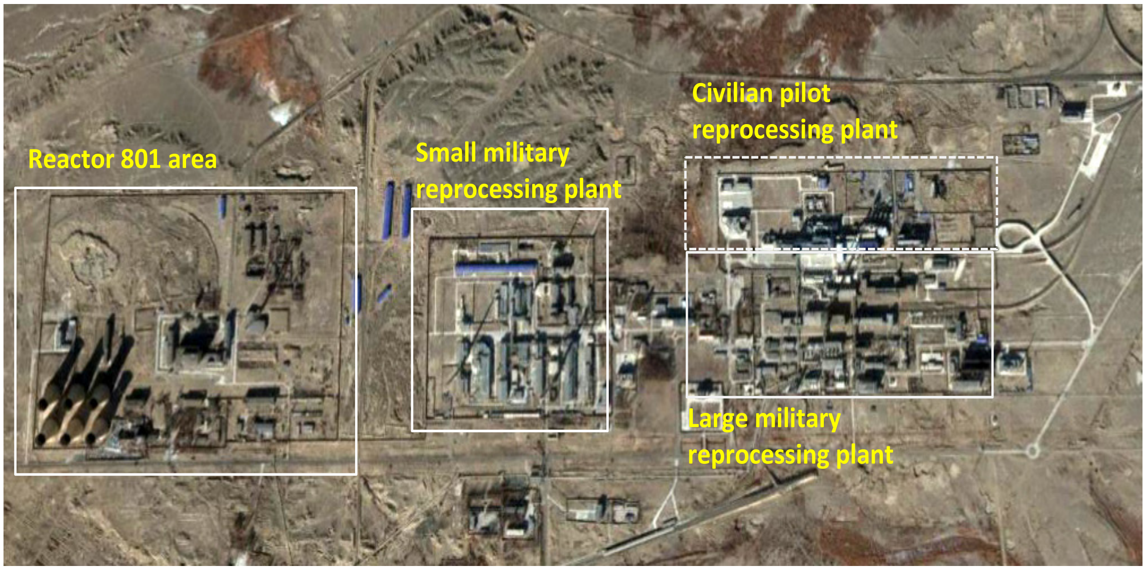

Figure 2.05: Overview of the Jiuquan nuclear complex (Plant 404). Satellite image from 31 Aug 2007. Credit: DigitalGlobe and Google Earth. The civilian pilot plant is immediately adjacent to the military reprocessing plant.

China's Civilian Reprocessing Pilot Plant

In July 1986, as one key project of the national high-technology R&D "863 Program" initiated in March 1986, the State Council approved the construction of a pilot civilian reprocessing plant at the Jiuquan nuclear complex, known as Plant 404 (as shown in figure 2.04). The design of the civilian pilot plant was based on experience with PUREX test facilities developed in the 1960s for the nuclear weapon program. This civilian pilot plant includes a main reprocessing facility with a maximum capacity to process 400 kg of spent fuel per day (the same as that of the military intermediate pilot facility).[124] The facility's reprocessing capability is estimated to be 50 tons of fuel/year.[125] The plant also includes a hot cell laboratory with a capacity of 0.9 kg of HEU spent fuel/day, and the CWSF.[126]

Construction of the plant started in 1998 and finished in 2005. The construction process encountered difficulties, delays, and higher-than-expected costs. Finally, 24 years after the project's approval, in December 2010, a hot test was conducted. However, due to technical problems, the plant operated only about the equivalent of 14 days during its first six years, from December 21, 2010 to December 31, 2016, an average capacity factor of about 0.4%.[127]

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124. National Nuclear Safety Administration (NNSA), Annual Report 2006, (in Chinese).
125. Zhang Donghui, "Status of China National SFR Program" (presentation, International Workshop on Prevention and Mitigation of Severe Accidents in Sodium-Cooled Fast Reactors, Tsuruga, Japan, June 12-13, 2012).
126. Jiang Yunqing, "China's Spent Fuel Treatment: The Present Status and Prospects," Status and Trends in Spent Fuel Reprocessing, Proceedings of an Advisory Group Meeting (Vienna: IAEA, August 1999), http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/047/30047646.pdf."
127. Hui Zhang, "On China's Closed Fuel Cycle Strategies," presented at the Institute of Nuclear Materials Management 59th

According to one conference report, the pilot plant began operating normally in 2017.[128] If so, it would produce 500 kilograms of plutonium per year. However, others have argued that in the three years from 2017 to 2019 China finally completed the task of reprocessing 50 metric tons of spent fuel accumulated between December 2010 to 2019. Thus, China may have reached a civilian plutonium stockpile of at least 500 kg by 2019, for an average capacity factor of about five percent between December 21, 2010 and December 31, 2019. However, China has not submitted official reports to the IAEA since 2017.

The Jiuquan complex also hosts a pilot mixed-oxide (MOX, uranium-plutonium) fuel fabrication facility (0.5 ton plutonium per year capacity). Its purpose is to supply fuel for China's Experimental Fast Reactor (CEFR). But the CEFR, which reached criticality in July 2010, had not used any MOX fuel as of late 2019. It started up with HEU instead, with an initial core of about 240 kg of uranium enriched to 64.4 percent U-235, provided by Russia. CIAE expected to load the CEFR with MOX fuel before 2020. China had approved several research projects on the pellets, clad, rods, and subassemblies for this fuel, and planned to load test rods of MOX into CEFR for irradiation before 2017.[129]

The 200 tHM/year Demonstration Reprocessing Plant

In December 2011, China's National Energy Administration (NEA) issued the 12th five-year energy plan that included a call for a reprocessing "demonstration" project with a planned capacity of 200 tHM/year to be completed by 2020.[130] In 2012, CNNC's "Long Teng 2020 (Dragon Soars 2020)" technology innovation plan included the demonstration plant as one key project. The central government eventually approved the demonstration plant in early 2015. In July 2015, CNNC started construction in Jinta, Gansu Province, about 100 km from the Jiuquan pilot plant.[131] The demonstration reprocessing plant is to be commissioned in 2025.

While there were news coverages of the groundbreaking ceremony of the CNNC Gansu Nuclear Technology Industrial Park, information on the location and construction progress has been scarce. Based on available information and satellite imagery, however, we can locate the site and identify the key facilities under construction (see figure 2.06).[132]

It is reported that a water pipeline started construction in June 2015 and completed in August 2017. It has a total length of 125.68 km that began at the Jiuquan Plant 404 and ended at the demonstration plant in Jinta.[133] A dedicated highway from Jiayuguan city to the demonstration plant, with a construction mileage of about 61km, started construction in July 2016 and completed in October 2017.[134] As shown in the satellite images, by November 2019, the buildings hosting spent fuel reception pools seem finished. The high stack of the reprocessing plant is completed. The main processing builds were at an intensive construction

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Annual Meeting, Baltimore, MD, July 2018.
128. Gu Zhongmao, China Institute of Atomic Energy, "Safe and Secured Management of Spent Fuel in China," 16th Beijing Seminar on International Security, Shenzhen, China, 17 October 2019.
129. Zhang, "Status of China National SFR Program, "op.cit.
130. National Energy Administration, National Energy and Technology Plan during the 12th five-year period (2011-2015), March 2011, http://www.nea.gov.cn/131398352_11n.pdf.
131. Yue Qi, "China establishes its first national nuclear technology industrial park and begins industrialization of spent fuel reprocessing in Gansu," National Business Daily, August 25, 2015. http://www.nbd.com.cn/articles/2015-08-25/940911.html.
132. Hui Zhang, "Pinpointing China's New Plutonium Reprocessing Plant," Bulletin of the Atomic Scientists, May 5, 2020. https://thebulletin.org/2020/05/pinpointing-chinas-new-plutonium-reprocessing-plant/.
133. http://www.beitaipipes.com/news_detail/newsId=242.html.
134. http://www.hewuyuan.com/news/show-1182.aspx.

stage. In late 2019, the company started to order equipment for the reprocessing facility.[135] Those building activities and equipment purchases show the plant could complete its civil engineering stage and enter the equipment installment stage in 2020. However, the current COVID-19 pandemic may affect its progress.

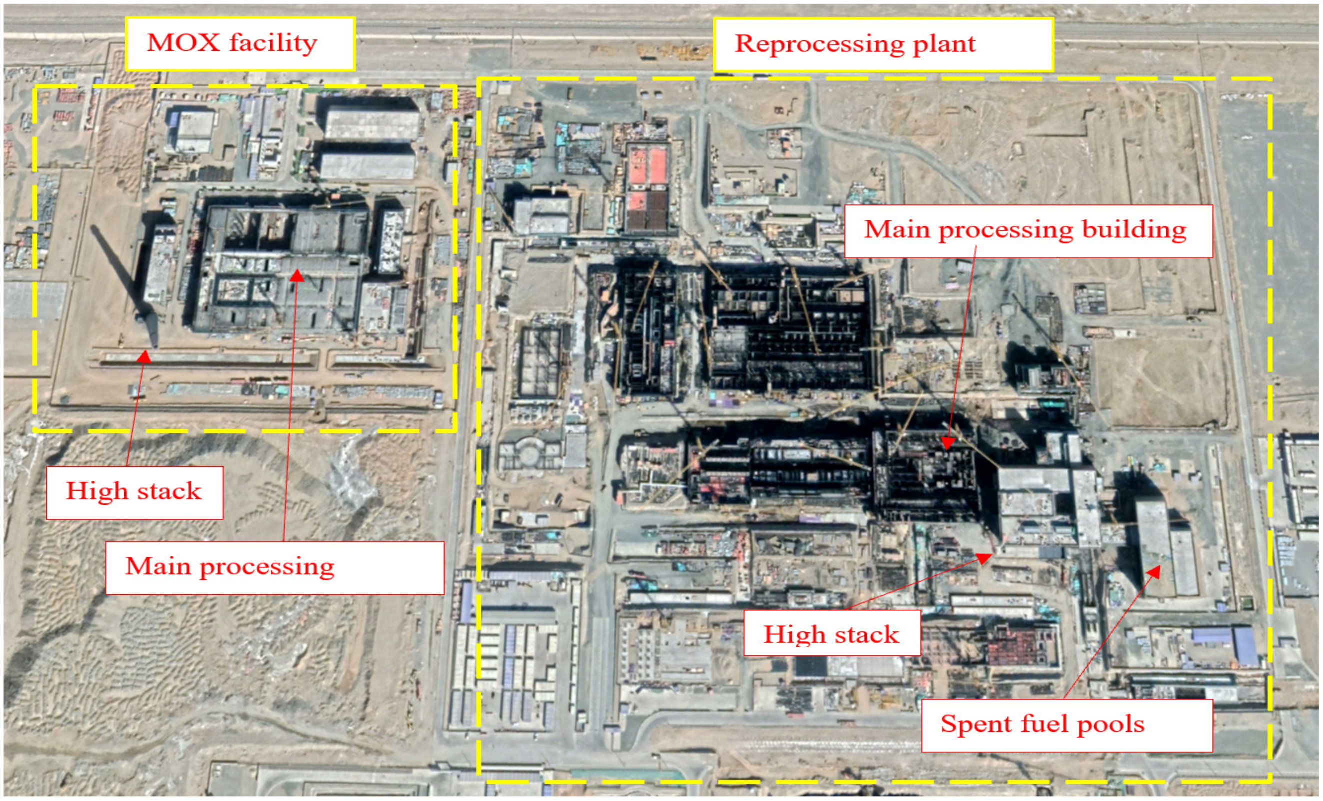

Figure 2.06: The demonstration reprocessing and MOX facilities under construction at Jinta, Gansu. Satellite image from March 12, 2020 (Coordinates: 40°19'29.74"N 98°30'53.30"E). Credit: Maxar Technologies and Google Earth.

<u>*The Demonstration MOX Fabrication Line*</u>

CNNC is also building a demonstration MOX fuel fabrication line with a capacity of 20 tons/year near the demonstration reprocessing plant. The 200 tHM/year reprocessing plant and the 20 t/year MOX fuel fabrication plant would provide operational support for the demonstration CFR-600 reactors.

The MOX plant broke ground in June 2018.[136] As shown in satellite images, by November 2019, the main buildings likely to host the MOX production line were at an intensive construction stage. The high stack of the facility is completed. In 2019, the company started to order equipment for the MOX fabrication line. The company posted a bidding period between August 29 and September 3, 2019, for purchasing

135. http://www.weain.mil.cn/cggg/jggg/1201435778442936321.shtml?v=20191203084919.
136. http://www.baopo.net/news/show-htm-itemid-807.html.

the package of chemical analysis equipment. The equipment should have been received within 2019.[137] It is expected the reprocessing and MOX facilities could complete the civil engineering stage and enter the equipment installment stage in 2020. It is expected to be operational by 2025.

Negotiating an 800 tons/year Commercial Reprocessing Plant

As stated earlier, the Chinese government shifted its nuclear power development policy from "moderate development" to "active development" in 2004. Anticipating a shortage of uranium supplies for China's faster nuclear power development, CNNC proposed plans to develop commercial reprocessing plants and breeder reactors. As the sole organization responsible for the back end of China's fuel cycle, CNNC emphasized that it wanted to be able to reprocess spent nuclear fuel from its commercial light-water reactors (LWRs), extract the plutonium, and use it to fabricate startup nuclear fuel for fast breeder reactors (FBRs).

In 2004, China Institute of Atomic Energy (CIAE) experts wrote to the national leadership regarding the urgency of developing commercial reprocessing technology, provoking a number of statements on the importance of the issue.[138] The Global Nuclear Energy Partnership (GNEP) program, launched by the U.S. Department of Energy (DOE) in 2006, further encouraged CNNC's plans for a closed fuel cycle by proposing the development of commercial reprocessing technologies.[139]

Since 2007, CNNC has been negotiating with France's Areva for the purchase of a commercial reprocessing plant with a capacity of 800 tHM/year. In June 2015, the negotiation made significant progress: it completed the technical discussions and started negotiations on business aspects.[140] However, it seems both parties yet to have reached an agreement on price.

The 800 tHM/yr plant could be sited at the east coastal area. In July 2015, CNNC Ruineng started working on a preliminary evaluation of the seismic safety at two pre-selected coastal sites for the proposed plant with a spent fuel storage capacity of 6000 tons with two phases and reprocessing of 800 tHM/yr. The evaluation work was planned to be finished by September 30, 2015.[141] One of the pre-selected sites for the reprocessing plant, in Lianyungang, Jiangsu province, was cancelled in August 2016, however, after thousands of people protested.[142] Recently, CNNC nuclear experts suggested the siting issue would be solved soon, and the large plant would soon start construction. However, some Chinese nuclear experts argue it may take longer time to have a final deal.

137. http://gansu.okcis.cn/dnww20190828173130625817.html.
138. Yuan Ying, "A Small Gobi Town "Devoured" International Nuclear Waste," (in Chinese), Southern Weekend, January 17, 2011, http://www.infzm.com/content/54595.
139. Gu Zhongmao, Yan Shuheng, and Hao Dongqin, "Urgency for Building Chinese Commercial Reprocessing Plant," China Nuclear Industry, No. 2 (2008).
140. France-China: AREVA Signs Three Agreements with its partners CNNC, CGN and EDF, June 30, 2015. http://www.areva.com/scripts/news/publigen/content/templates/Show.asp?P=10556&L=EN.
141. "Sino-French nuclear negotiations move forward and evaluation of the seismic safety at coastal sites starts," (Chinese) August 25, 2015. http://www.bjztb.gov.cn/news/201508/t9420808.htm.
142. Chris Buckley, "Thousands in Eastern Chinese City Protest Nuclear Waste Project," *New York Times*, 8 August 2016. https://www.nytimes.com/2016/08/09/world/asia/china-nuclear-waste-protest-lianyungang.html?_r=0.

2. China's Fast Reactors Programs: Current Practices and Outlooks

China's Experimental Fast Reactor (CEFR)

The CEFR program was also part of the national high-technology R&D "863 Program". The project received government approval in 1995. It is a sodium-cooled, experimental fast reactor with a power capacity of 20 Megawatts-electric (MWe) (65MWt). CNNC began construction on the CEFR in May 2000.[143] However, the CEFR met a multitude of difficulties resulting in a long construction time. The total capital cost estimate of CEFR was adjusted two times, with each new figure doubling the previous one. After the detailed design was finished, the final capital cost was roughly 3.7 times the original estimate.[144]

The CEFR went critical in July 2010, ten years after the start of construction, and had 40 percent of its full power incorporated to the grid by July 2011. However, the reactor was online for only 26 hours during 2011—producing the equivalent of one full-power hour—and then was not connected again during 2012 or 2013.[145] After three years since its last test, the CEFR successfully operated at full capacity for 72 hours on December 15-18, 2014 It took about 19 years from the project approval in 1995 to achieving operation at full capacity in 2014, with intermittent operations between 2015 and 2016 for R&D. It did not operate between 2017 and 2018. Cumulatively, it has operated only about 26 equivalent full-power days between July 2011 and 2018.[146] It has operated intermittently since then, for a cumulative 26 equivalent full-power days between July 2011 and 2018. Its lifetime capacity factor from 2011-2018 was, therefore, only about 1 percent.

The CFR-600 Demonstration Fast Reactor

After China adopted "active" development of nuclear power around 2004, CNNC promoted the development of fast reactors in China. In 2010, CIAE experts proposed deploying several demonstration fast reactors at Sanming in Fujian province, including two 800 MWe BN-800 FBRs from Russia by 2018 and one indigenous 1000 MWe China Demonstration Fast Reactor (CDFR) by 2022. However, CNNC in 2013 began focusing on the development of the indigenous 600-megawatt China Fast Reactor (CFR-600) as a demonstration project.

The CFR-600 preliminary and detailed designs were completed in 2016 and 2017 respectively. In December 2017, the construction of CFR-600 started at Xiapu, Fujian (see figure 2.07). The CNNC plans to operate it in 2023. On January 18, 2020, CNNC reported the first CFR-600 reactor accomplished a

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143. See, Xu, "Fast Reactor Development for a Sustainable Nuclear Energy Supply in China," op.cit.

144. Yang Hongyi, "Economic Issues of Fast Reactor in China" (presentation, Technical Meeting on Fast Reactors and Related Fuel Cycle Facilities with Improved Economic Characteristics, Vienna, Austria, September 11-13, 2013, https://www.iaea.org/NuclearPower/Downloadable/Meetings/2013/2013-09-11-09-13-TM-NPTD/7.yang.pdf).

145. International Atomic Energy Agency, "China Experimental Fast Reactor," Power Reactor Information System, http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=1047. Xinhua News, "China experimental fast reactor runs at full capacity," December 19, 2014, http://www.cs.com.cn/english/ei/201412/t20141219_4595461.html.

146. It is reported the reactor generated a total of 5790.4 MWh from 2011 to 2015, i.e. about 12.06 equivalent operation days. Moreover, based on the described operation in 2014, I estimate that it was about 8.12 equivalent operation days in 2014 (see, Yang Hongyi, Fast Reactors Progress and Cooperation with French, the 2nd Black End Seminar in Beijing, May5, 2015. http://china.areva.com/home/liblocal/docs/China%20Offer/2nd%20Back%20End%20Seminar%20in%20Beijing%202015/5_%E6%9D%A8%E7%BA%A2%E4%B9%89_En%20Ch.pdf. Thus, about 3.94 equivalent operation days was in 2015. Finally, it was reported the reactor operated 23 days at the power of 39 MWt in 2016, i.e. about 13.8 equivalent operation days (see, Zhang, The Development of Nuclear Energy and FR in China).

key milestone -- ending civil engineering and entering the equipment installation stage, 13 days ahead of schedule.[147]

The 200 tons/year demonstration reprocessing plant would supply plutonium for the MOX fuels to the CFR-600 reactor. But Russian TVEL will supply the initial core and reloads with HEU fuels during the first seven years of the reactor's operation.[148]

Also, CNNC is actively preparing to construct the second CFR-600.[149] The second CFR600 is to have the same design as the first and is to be located at the west of the first reactor (as shown in figure 2.07). [150] The early site preparation work was completed in 2019. It is expected the first concrete will be poured for the second CFR-600 by the end of 2020 and that it will be commissioned around 2026. However, the COVID-19 pandemic could have an impact on the construction timeline.

Figure 2.07: Satellite image over CFR-600 reactor site. Satellite image taken December 11, 2019 (Coordinates: 26°47'59.78"N 120° 9'12.00"E). Credit: Maxar Technologies and Google Earth.

147. http://www.cnnc.com.cn/cnnc/300555/300558/542805/index.html.
148. http://world-nuclear-news.org/Articles/TVEL-to-supply-fuel-for-Chinas-fast-neutron-react.
149. Hui Zhang, "China is speeding up its plutonium recycling programs," Bulletin of the Atomic Scientists, Vol.76, No.4, 2020.
150. http://jr.ejmrh.com/mcjhtml/equipmentReform/20191119/140245.html.

Proposals for Larger Commercial Fast Breeder Reactors

Since 2013, CIAE experts have also proposed developing the first commercial fast reactor—a 1000 MWe CFR-1000 or 1200 MWe CFR-1200 -- based on the experience they will gain from the CFR-600. CNNC plans to complete the pre-concept design and make a decision to proceed by 2020, then finish the conceptual and preliminary designs by 2024 and 2028, respectively. It is to start construction in 2028 and operate in 2034.[151] Nonetheless, China's government has not officially either approved or rejected the plan. Currently, it is not clear when, or indeed if, the project will go forward.

The head of the fast reactor division of CIAE states that the deployment of commercial fast reactors in China will depend on several factors. Among these factors are the cost of uranium; safety validation and the feasibility of an inland site; and the cost of electricity from an FBR compared to that of a coal power plant.[152] Before commercializing fast neutron reactors, China would need to construct a commercial scale breeder fuel fabrication plant along with a reprocessing plant for breeder reactor fuel.

3. Projections for Stockpiling of Reactor-Grade Plutonium

Projections of Cumulative Plutonium Separated from PWR Spent Fuels

Based on China's reprocessing programs, figure 2.07 (based on the assumptions in table 2.03) project four different scenarios for China's reactor-grade plutonium separated from its PWR spent fuel through 2040. As the high-production scenario, it assumes that China separates 0.5 tons of plutonium per year by its pilot reprocessing plant from 2020 to 2040; that the 200 t/year demonstration reprocessing plant is operational in 2025 and separates 2 tons/year since then, and the 800 tons/year commercial reprocessing plant comes online in 2035 and separates 8 tons/year thereafter. [153]

151. Yang Hongi, Fast Reactors Progress and Cooperation with French, the 2nd Black End Seminar in Beijing, May5, 2015.
152. Zhang, "Fast Reactor Development Strategy In China."
153. Given that the design and construction of commercial reprocessing plants involve very complicated and technical systems engineering, CIAE experts suggest that it would take at least 15 years to progress from a completed design to an operational plant (see, Gu Zhongmao, Yan Shuheng, and Hao Dongqin, "Urgency for building Chinese commercial reprocessing plant," China Nuclear Industry, No. 2, 2008). Even if the plant starts construction in 2020, it is optimistic to project that it will be commissioned in 2035.

Table 2.03: Scenarios and assumptions for cumulative plutonium separated from PWR spent fuels from 2020 to 2040

Scenarios	Assumptions
Case 1 (Full)	1) The pilot plant operates at full capacity (0.5 t pu/yr) from 2020 to 2040 and had a stock of 0.5 t separated plutonium by 2019. 2) The demo reprocessing plant operates at full capacity (2 t pu/yr) from 2025 to 2040. 3) No 800 tHM/yr reprocessing plant is built.
Case 1 (Half)	The pilot and demonstration plants operate at half capacity of Case 1 (Full).
Case 2 (Full)	1) The same assumptions as in Case 1(Full), except the 800 tHM/yr reprocessing plant is built. 2) One 800 tHM/yr reprocessing plant operates at full capacity (8 t pu/yr) from 2035 to 2040.
Case 2 (Half)	The pilot, demonstration and 800 tHM/yr plants operate at half capacity of Case 2 (Full).

Thus, under the high scenario of separated plutonium production (as the case 2 (Full) shown in figure 2.08), approximately 18 tons and 91 tons of separated plutonium would be produced cumulatively through reprocessing PWR spent fuel by 2030 and 2040, respectively. As the low-production scenario (i.e., as the case 1 (Half) shown in figure 2.08), it assumes the pilot and demonstration reprocessing plants operate at half capacity, and the large reprocessing is not built. Consequently, approximately 9 tons and 22 tons of separated plutonium would be produced cumulatively by 2030 and 2040, respectively—still several times its current inventory of military plutonium for weapons, which is about 2.9 tons.

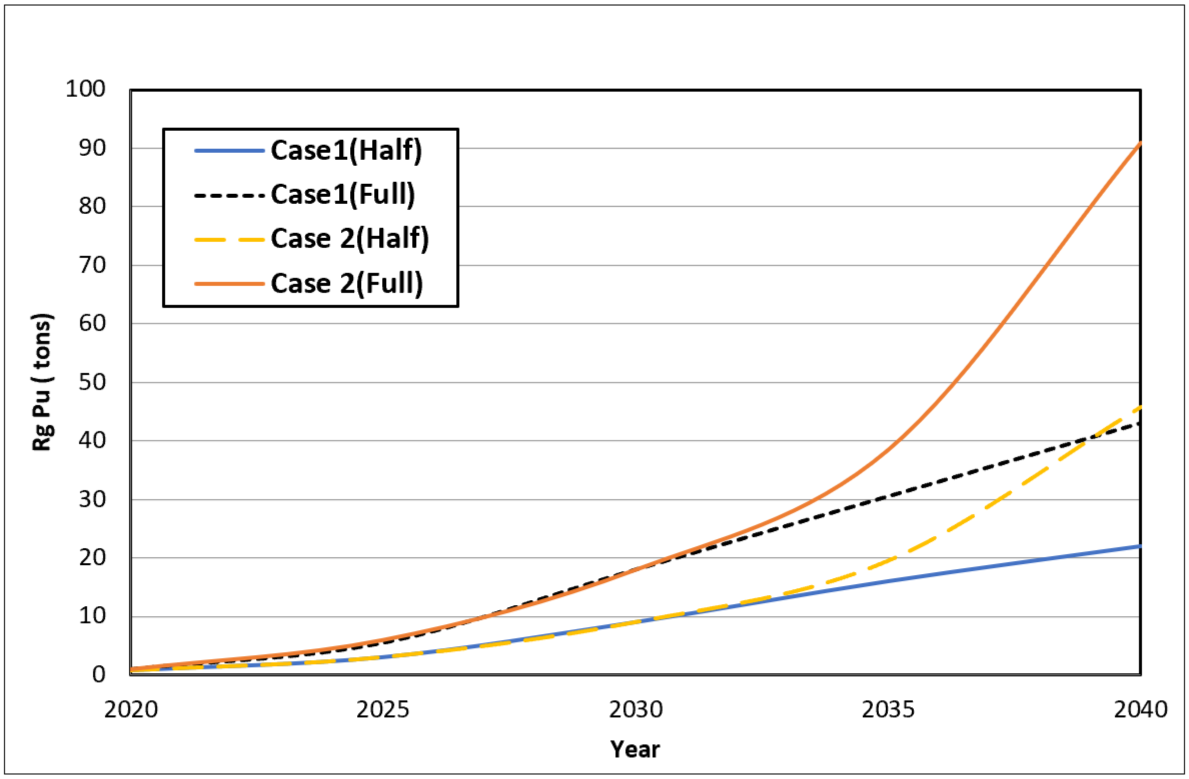

Figure 2.08. Projections of cumulative plutonium separated from PWR spent fuels from 2020 to 2040

<u>*Cumulative PWR Plutonium Used by Fast*</u>

Projections of how much the separated plutonium from PWR spent fuel are to be used in China's fast reactor programs are based on following assumptions: (1) CEFR continues using HEU fuel until 2024, then uses MOX fuel from 2025 through 2040. Its initial core requires plutonium of 150 kg, [154]and the replacement is about 150 kg plutonium/year. [155] (2) The first CFR-600 is commissioned in 2023 and uses the Russian-supplied HEU for the first seven years. It starts in 2030 using MOX fuel supplied from the 200 tons/year demonstration reprocessing plant. It requires a two ton initial core inventory and one ton/year replacement each year.[156] CIAE fast reactor experts suggest a beginning recycling time of two years for the MOX-fueled FBR.[157] If so, one CFR600 would need about an inventory of four tons of PWR plutonium. However, as a conservative estimate, it assumes here the recycling time is five years. Thus, the CFR-600 would need an inventory of seven tons of PWR plutonium. (3) The second CFR-600 is assumed to start construction by the end of 2020 and operate in 2026. Like the first CFR-600, it starts using MOX fuel in 2030 with the same assumptions.

154. Xu,"Fast Reactor Development for a Sustainable Nuclear Energy Supply in China," op.cit.
155. Communications with CIAE nuclear experts, June 2017.
156. Regarding CFR 600 MOX fuel reloads: as an estimate: assuming the reactor thermal power is 1500 MWth; the burnup is about 100 MWt-day/kg. If the capacity factor is taken 60-80 percent, the MOX fuel reload is about 3.29-4.38 tons/year. Assuming the MOX fuel is with plutonium percentage of 25%, thus the annual plutonium requirements would be about 812-1095 kg/year.
157. Communications with CIAE nuclear experts, June 2017.

Consequently, as a high case of plutonium use, assuming the CEFR and the two CFR-600 fast reactors operate at full design capacity as discussed above, then, as shown in figure 2.09, approximately 4.9 tons and 16.4 tons of separated plutonium would be used cumulatively by 2030 and 2040, respectively. As a low-use case of plutonium, assuming the CEFR and two CFR-600 fast reactors operate at half of designed capacity, then, approximately 4.5 tons and 10.3 tons of separated plutonium would be used cumulatively by 2030 and 2040, respectively.

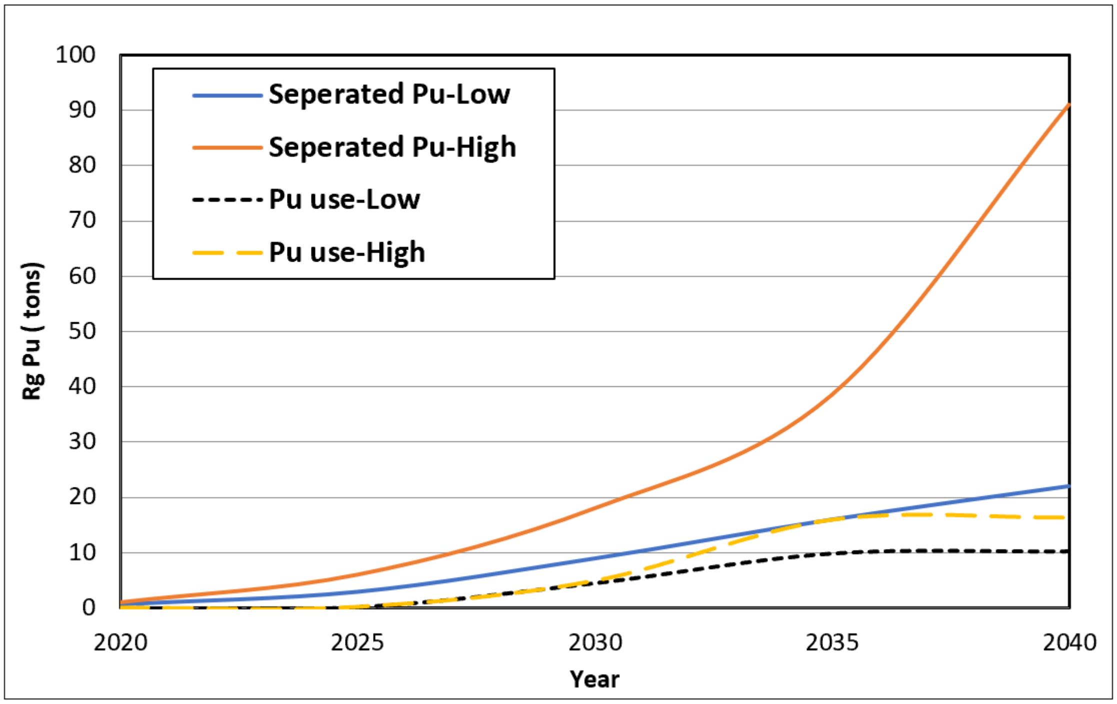

Figure 2.09: China's projected cumulative PWR plutonium produced and used in fast reactors 2020-2040. The figure shows clearly even the low case of plutonium produced could be large enough to meet the planned fast reactor programs through 2040.

It should be noted that, as shown in figure 2.08, even the low case of separated plutonium production is large enough to meet the high case of plutonium uses for FBRs. Thus, it would have no sense for China to build an 800 tons/year reprocessing plant in the near future.

However, if China builds an 800 tons/year reprocessing plant in 2035 as discussed, it could amass a stockpile as large as around 80 tons of separated plutonium by 2040. Most likely, China would have as large a stock of reactor-grade plutonium as Japan and France have done. China has long worried about Japan's reprocessing and recycling programs that could have an option for weapons once needed,[158] however, China's own programs would only encourage others.

158. Hui Zhang, "China Worries about Japanese Plutonium Stocks," *Bulletin of the Atomic Scientists,* Jun 17, 2014.

4. A Discussion of Weapon-Grade Plutonium Produced by Fast Reactors

In the 1980s, China stopped plutonium production for weapons and closed all plutonium production reactors and associated reprocessing facilities. While it is unthinkable politically for China to resume plutonium production for weapons, there are still discussions to be had about their technical capacity.

Indeed, recently some Western experts on arms control and nonproliferation have raised concerns about the possibilities that China could use the reactor grade plutonium in its FBRs to produce weapon-grade plutonium in the breeder blankets.[159] It is estimated that each CFR-600 reactor could produce about 0.2 tons WgPu/year, [160] enough for about 50 warheads/year. If so, the two CFR-600 reactors could produce about 0.4 tons WgPu/year (about 100 warheads/year). If they start to use MOX fuel from 2030, a total about four tons of weapon-grade plutonium could be produced by 2040, about 1.4 times China's current inventory of military plutonium of 2.9 tons.

Finally, it should be noted that even though China has the technological capacity and economic resources to produce more plutonium and HEU for weapons if it wants, such a production would be essentially constrained by its long-standing nuclear policy. Since its first nuclear explosion, China has maintained a nuclear policy that features a no-first-use pledge and a "lean and effective" nuclear force, and strives to avoid a costly nuclear arms race.

Under the guidance of its self-defense nuclear strategy, China is likely to continue its nuclear modernization to assure a reliable retaliation under any circumstance. U.S. missile defense plans will be a major driver for China's nuclear weapon modernization, which includes expanding their nuclear arsenal with more and better ICBMs.[161] China's existing stockpile of fissile material would be sufficient for its current modernization programs. However, if the United States moves forward with their plans for missile defense and space weapons, China may decide it needs more nuclear missiles in order to maintain its deterrence capability which might require more plutonium and HEU to fuel those weapons. A calculation of this measure would drive China to resume fissile materials production for weapons and undermine possible Chinese support for FMCT negotiations.

Finally, China should address international concerns about the proliferation implications of the development of centrifuge technology, including their need for more transparency of its centrifuge development plans and capacities. Also, China needs to keep its plutonium recycling programs more transparent including timely reporting of its stockpile of civilian plutonium like they did before 2016.

159. Some nuclear nonproliferation experts are further concerned that if China wanted to produce more weapon-grade plutonium, it could technically use some of its power reactors including the Candu-6 reactors or the 1GWe PWRs. Moreover, even the reactor-grade plutonium can be still weapon-usable (see details: Henry Sokolski, Nuclear Proliferation: How Bad Might It Get? Nonproliferation Policy Education Center, Presentation at Crystal City Gateway Marriott Arlington, Virginia January 14, 2020, http://npolicy.org/event_file/Nuclear_Proliferation,_How_Bad_Might_It_Get_220120_1551.pdf). Thus, even without running the 800 tons/year commercial reprocessing plant, the 200 tons/year demonstration plant, once operated, could be used to separate a significant amount of plutonium either weapon- or reactor- grade plutonium that both can be for weapons purpose. However, some Chinese argue such scenarios are unthinkable politically.

160. It is estimated that the Indian 500 MWe (1250MWth) Prototype Fast Breeder Reactors could produce up to 140 kg of weapon-grade plutonium each year. See details in Alexander Glaser and M.V.Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," Science and Global Security, 15:85-105,2007. Scaling from this Indian breeder model to China's CFR-600 (with 1500 MWth and a breeding ratio of 1.15), each CFR-600 could produce about 0.2 tons of weapon-grade plutonium each year.

161. Hui Zhang, "China's nuclear modernization: assuring a second-strike capability," Correspondence, *The Nonproliferation Review*, 24:3-4, p.215-218, 2018, https://www.tandfonline.com/doi/pdf/10.1080/10736700.2018.1431186?needAccess=true.

China should learn from the experiences of other countries that have prematurely launched large reprocessing programs with the expectation that the commercialization of breeder reactors would follow—but did not. China has no convincing rationale for rushing to build commercial-scale reprocessing facilities or plutonium breeder reactors. China should postpone the large reprocessing-plant project, and take an interim-storage approach. Following this approach will give China a substantial opportunity to carefully develop a long-term policy for the nuclear fuel cycle.

Chapter 3

China's Current Stocks of Separated Plutonium and Possible Growth to 2040

Gregory S. Jones[162]

All plutonium, even reactor-grade plutonium, can be used to manufacture nuclear weapons.[163] Estimates of China's current stocks of separated plutonium are uncertain and tend to be influenced by a circular argument. Initially, China was thought to have a relatively small nuclear weapon stockpile and therefore estimates of China's fissile material stocks were correspondingly low. However, when some analysts suggest that perhaps China's stockpile of nuclear weapons may be larger than is generally thought, this suggestion is dismissed by the argument that China does not have enough fissile material for a large nuclear weapon stockpile.

A related issue is the almost universal claim that China has not produced any fissile material (both highly enriched uranium [HEU] and plutonium) for nuclear weapons since about 1990. This would put China in step with countries such as the U.S., who have formally stated that they no longer produce weapon related fissile material. However, China has never stated that it has ended such fissile material production and the evidence that it has is not very strong. Indeed, this claim is almost certainly untrue since China very likely has an undetected tritium production reactor. This reactor is very probably producing at least some weapon-grade plutonium. Further, if China has an undetected tritium production reactor, it could also easily have an undetected plutonium production reactor.

Given these issues, this paper will examine the likely size of China's separated plutonium stocks, taking into full account the uncertainties in such estimates. The paper will generate new estimates of China's current (2020) and future (to 2040) stocks of both weapon-grade and non-weapon-grade plutonium and compare them to the estimates of other analysts.

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162. This paper was written for the Nonproliferation Policy Education Center. Though the author is also a part-time adjunct staff member at the RAND Corporation, this paper is not related to any RAND project and therefore RAND should not be mentioned in relation to this paper. I can be reached at GregJones@proliferationmatters.com.
163. I have extensively discussed the issue of reactor-grade plutonium in Gregory S. Jones, *Reactor-Grade Plutonium and Nuclear Weapons: Exploding the Myths*, Nonproliferation Policy Education Center, 2018 https://nebula.wsimg.com/3fd1e3cfbbf101d6c4f562e17bc8604c?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1 and Gregory S. Jones, "Reactor-grade plutonium and nuclear weapons: ending the debate," *The Nonproliferation Review*, February-March 2019 Vol. 26, No. 1-2. The technical appendix to the latter work can be found here: https://nebula.wsimg.com/4eb6ba13bee5765c8e2aec7d658c7cde?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.

Weapon-Grade Plutonium

Current Stockpile 2020

China is believed to have had two graphite moderated plutonium production reactors. The reactor at Jiuquan started operation in late 1967 and ended operation in late 1986. The reactor at Guangyuan started operation near the beginning of 1974. When the Guangyuan reactor ended production is unknown but it is assumed to have been sometime in the 1980s. Analysts generally believe that these two reactors were China's only source of weapon-grade plutonium and that China has not added to this stockpile since about 1990.

Calculating how much plutonium was produced by these two reactors is fairly straightforward.[164] One calculates the product of the reactors' power level times the length of time that the reactors operated. The result is in megawatt-days. One multiplies this number by the amount of plutonium that would be produced per megawatt-day to get the total amount of plutonium produced.[165]

Despite the seeming simplicity of this calculation, estimates of China's weapon-grade plutonium stockpile (even those by the same analyst) have varied substantially. The most recent estimate was made by Hui Zhang of Harvard's Belfer Center.[166] His estimate is 2.9 metric tons plus or minus 0.6 metric tons (2.3 to 3.5 metric tons). However, in 2010 this same analyst estimated the stockpile as only 1.8 metric tons plus or minus 0.5 tons (1.3 to 2.3 metric tons).[167] A similar swing in estimates but in the opposite direction, was made by David Albright of the Institute for Science and International Security. In 2014 he estimated the stockpile as 1.9 metric tons plus 0.5 and minus 0.3 metric tons (1.6 to 2.4 metric tons).[168] In 2005 he estimated the stockpile to be 2.8 metric tons with the 95th percentile being 3.2 metric tons and the 5th percentile being 2.3 metric tons.[169] In 2003, David Wright and Lisbeth Gronlund of the Union of Concerned Scientists, estimated the stockpile to be between 2 and 5 metric tons.[170]

This wide range of estimates illustrates that the uncertainties involved are larger than some of the estimates suggest. There are a number of reasons for this significant uncertainty including the power level of these reactors and how well they operated. I do not intend to enumerate all of the factors that contribute to this uncertainty but as an example, I will describe one of the uncertainties that produces a large variation in how much weapon-grade plutonium China might possess. According to Zhang's most recent estimate, the reactor at Guangyuan could produce 200 kilograms of plutonium per year by the late 1970s. He assumes that the reactor only produced at full capacity through 1979. He then assumes that it produced at

164. This paper as well as the work of other analysts, assumes that China separated all of the weapon-grade plutonium from the spent fuel soon after it was discharged from the reactor.
165. Depending on the reactor design and fuel burnup, this factor can vary between about 0.80-0.95 grams per megawatt-day for a natural uranium fueled reactor producing weapon-grade plutonium.
166. Hui Zhang, "China's Fissile Material Production and Stockpile," International Panel on Fissile Materials, 2017. http://fissilematerials.org/library/rr17.pdf.
167. Hui Zhang, "China's HEU and Plutonium Production and Stocks," *Science and Global Security*, Vol. 19, 2011. https://www.belfercenter.org/sites/default/files/legacy/files/huizhangSGS2011.pdf.
168. David Albright and Serena Kelleher-Vergantini, "Military Highly Enriched Uranium and Plutonium Stocks in Acknowledged Nuclear Weapon States," Institute for Science and International Security, November 3, 2015, p. 6. https://isis-online.org/uploads/isis-reports/documents/Military_HEU_and_Pu_Stocks_in_Acknowledged_NWS_November3_2015_Final.pdf.
169. David Albright and Corey Hinderstein, "Chinese Military Plutonium and Highly Enriched Uranium Inventories," Institute for Science and International Security, June 30, 2005. https://isis-online.org/uploads/isis-reports/documents/chinese_military_inventories.pdf.
170. David Wright and Lisbeth Gronlund, "Estimating China's Production of Plutonium for Weapons," *Science and Global Security*, Vol. 11, 2003. http://scienceandglobalsecurity.org/archive/sgs11wright.pdf.

half that rate to the latter part of 1984 and then stopped producing weapon-grade plutonium before it was shut down. However, there is only some suggestive information to support this view. The reactor could easily have run at full capacity until 1990. This would result in an additional 1.5 metric tons of weapon-grade plutonium. Whether the reactor actually ran until 1990 is unknown, but this example illustrates the degree of uncertainty in these estimates.

All of these analysts assume that however much weapon-grade plutonium China has produced, this production ended by about 1990. However, China's continuing need to produce tritium for its nuclear weapons suggests that this is probably not the case and that production is likely continuing today.

China's Tritium Production and Requirements

Tritium is a vital component of all modern nuclear weapons. Tritium makes it possible to produce boosted primaries in thermonuclear weapons. According to the British, such primaries are "immune" to predetonation, which helps ensure that the weapons will produce the desired yield.[171] It is known that all of the weapons in the U.S., British and French nuclear arsenals today are two-stage thermonuclear weapons that use boosted primaries.

Since tritium has a half-life of 12.3 years, each year 5.5% of the tritium decays away and continuing production is needed to maintain a tritium stockpile. Typically, nuclear weapon states such as the United States produce tritium by irradiating lithium in nuclear reactors. Natural lithium consists of two isotopes, lithium 6 and lithium 7. Lithium 6 comprises 7.5% of natural lithium and lithium 7 the other 92.5%. When irradiated by neutrons, it is the lithium 6 that produces tritium by the reaction: lithium 6 + neutron = tritium + helium 4.

Many experts assume that the lithium must be enriched (i.e. the percentage of lithium 6 increased) in order to produce tritium in a nuclear reactor, but there is no need. Since the thermal capture neutron cross section of lithium 6 is 942 barns and that of lithium 7 is 0.045 barns, when natural lithium is irradiated, 99.94% of the neutrons are absorbed by the lithium 6. The U.S. used natural lithium in the form of a lithium aluminum alloy to produce tritium in its plutonium production reactors during the 1950s.

China completed a plant to extract tritium from irradiated lithium aluminum targets in early 1967.[172] It produced its first tritium product in May 1968. Most countries boost their weapons by using a deuterium tritium gas mixture but China appears, at least initially, to have used a solid lithium deuterium tritium compound. It produced the first such material in 1972. Tritium first appeared in a Chinese nuclear test in September 1976.[173]

Albright as well as Wright and Gronlund ignore China's need to produce tritium and the impact it might have on China's plutonium production. Zhang has stated that China probably used its plutonium production reactor at Jiuquan to produce tritium, which would be consistent with U.S. experience.[174] Zhang reasonably estimates that during the interval that this reactor operated (1967-1986), the Chinese tritium

171. Lorna Arnold, *Britain and the H-Bomb*, UK Ministry of Defense, Palgrave, 2001, pp. 176-178.
172. JPRS Report: Science & Technology, China, "Selections from 'China Today: Nuclear Industry" JPRS-CST-88-002, January 15, 1988, p. 31.
173. Thomas C. Reed, "The Chinese nuclear tests, 1964-1996," *Physics Today*, September 2008. https://physicstoday.scitation.org/doi/pdf/10.1063/1.2982122.
174. Hui Zhang, "China's Fissile Material Production and Stockpile," International Panel on Fissile Materials, 2017, p. 29. http://fissilematerials.org/library/rr17.pdf.

requirements would only have been a few kilograms.[175] Since one kilogram of tritium equates to 79.3 kilograms of plutonium, tritium production would have only reduced China's plutonium production at this reactor by a few hundred kilograms, which is within his uncertainty bounds.

But the key question is how has China produced tritium since 1986. Zhang has suggested that perhaps China extracts tritium from the moderator of its two CANDU 6 heavy water moderated power reactors.[176] In prior work I discussed how much tritium could be extracted from the moderator of a CANDU 6 power reactor and concluded that South Korea has acquired a substantial stockpile of over 4 kilograms of tritium which has been extracted from its four CANDU 6 power reactors.[177] Each CANDU 6 reactor would produce about 135 grams of tritium in its moderator each year, so China's two reactors would produce about 270 grams per year which would be more than enough to meet its needs.[178]

However, there are substantial difficulties with Zhang's suggestion. China's first CANDU 6 power reactor did not start commercial operation until the end of 2002. This would mean that there would have been a 16 year interval where China did not produce any tritium. During this interval 59% of China's tritium would have decayed away. Further, as I have written, extracting the tritium from the moderator just when the reactor has started operation would be difficult since the tritium would be rather dilute. It would be much better to wait about 10 years when the tritium would be about eight times more concentrated.[179] But waiting this long would mean that China would not have produced any tritium for 26 years and 77% of its tritium stockpile would have decayed away. In addition, there is no evidence that China is actually extracting tritium from its CANDU 6 power reactors. Such a process would need specialized facilities and equipment.[180] There is no indication that such facilities exist.

Another possibility is that China is irradiating lithium in its commercial light-water power reactors. But this idea also has difficulties. The first of these reactors did not start commercial operation until eight years after the reactor at Jiuquan had shut down. Further, the high temperature of the coolant of a commercial power reactor means that lithium aluminum alloy targets cannot be used. Instead lithium targets in the form of lithium aluminate must be developed. Further the high temperature would cause the tritium to diffuse though most materials, including stainless steel, and special measures must be taken to contain it. The U.S. is producing tritium at a commercial light-water reactor, Watts Bar 1. However, this program has been plagued with difficulties and only after more than 20 years has it started achieving its goals.[181]

It is hard to escape the conclusion that China has operated an undetected tritium production reactor since at least 1986 and *it is continuing to operate this reactor today*. China's tritium requirements have increased significantly since the 1980s. Though in the early years of its nuclear weapon program not all of China's

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175. Ibid., footnote 153, p. 47.
176. Ibid., p. 18.
177. Gregory S. Jones, "Heavy Water Nuclear Power Reactors: A Source of Tritium for Potential South Korean Boosted Fission Weapons," February 29, 2016. https://nebula.wsimg.com/344f048726407b8951892db91c98a0b1?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.
178. Gregory S. Jones, "Do India and Pakistan Possess Boosted Nuclear Weapons? Tritium Supply Considerations," July 31, 2019, p. 3. https://nebula.wsimg.com/b2c3c9b49ad062fdf2c7a52be054c98c?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.
179. Ibid., p. 4.
180. K.M. Song et. al., "Introduction to Wolsong Tritium Removal Facility," *Transactions of the Korean Nuclear Society Autumn Meeting*, Pusan Korea, October 27-28, 2005. https://www.kns.org/files/pre_paper/17/173%EC%86%A1%EA%B7%9C%EB%AF%BC.pdf.
181. Gregory S. Jones, "The U.S. Program to Produce Tritium Using Commercial Power Reactors: 2019 Update." January 30, 2020. https://nebula.wsimg.com/b6c10a10aeb8d61f30037f6557a1facf?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.

weapons may have been boosted, the "Cox report" stated that China has gained access to advanced U.S. weapons designs and conducted nuclear weapon tests based on these designs.[182] As a result, China has likely phased out its unboosted weapons many years ago and all of its weapons today are two-stage thermonuclear ones that use boosted primaries. By comparison, France phased out its last unboosted nuclear weapon in 1993.[183]

I have estimated that in the past the U.S. used about 3.2 grams of tritium per nuclear weapon and that it is increasing the amount per weapon to 4.5 to 5.0 grams per weapon.[184] This increase is driven in part by uncertainties due to the lack of nuclear weapon testing. Given the relatively low number of nuclear tests that China has conducted, I assume that China uses 5 grams of tritium per weapon. The U.S. maintains a 5 year tritium reserve which increases the total amount of tritium required by about one-third. Given the potential difficulties in producing tritium, China may well want to keep a larger reserve. A 12.3 year reserve (tritium's half-life) would double the required amount of tritium per weapon to 10 grams. Given that China's arsenal could be about 300 weapons, this would result in the requirement for a 3 kilogram tritium stockpile.[185]

To compensate for tritium decay and maintain a constant stockpile, China would need to produce about 170 grams of tritium per year. Since China's nuclear weapon stockpile has been slowly growing, it would need to produce somewhat more than that. If a reactor were to produce only tritium and not any plutonium it would need to be fueled with HEU. A HEU fueled reactor with a power level of about 100 MW would produce about 190 grams of tritium per year which is about what China would currently need.[186]

If such a reactor existed, it would require 96 kilograms of HEU fuel each year.[187] Over the past 34 years this would amount to 3.3 metric tons of HEU. Estimates of China's HEU stockpile for nuclear weapons might need to take this HEU consumption into account. Though most analyst believe that China has stopped producing HEU for nuclear weapons, this is just an assumption on their part. Nothing prevents China from producing substantial amounts of additional weapon-related HEU using its indigenous centrifuge enrichment technology.

Due to the limited excess reactivity in a natural uranium fueled reactor and the large neutron absorption cross section of lithium, every reactor that has produced large amounts of tritium has used some sort of enriched fuel.[188] In its graphite moderated reactors at Hanford, the U.S. at one time used uranium that was enriched to 0.94%. To produce 190 grams of tritium per year using fuel with this enrichment would require

182. "Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the People's Republic of China," Select Committee, United States House of Representatives, U.S. Government Printing Office, Washington, 1999, pp. 60-95. https://www.govinfo.gov/content/pkg/GPO-CRPT-105hrpt851/pdf/GPO-CRPT-105hrpt851.pdf.

183. This was the AN-51 which was the warhead for the Pluton tactical ballistic missile.

184. Gregory S. Jones, "U.S. Increased Tritium Production Driven by Plan to Increase the Quantity of Tritium per Nuclear Weapon," June 2, 2016. https://nebula.wsimg.com/08a60104185a91e6db9008fb929a0873?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.

185. Hans M. Kristensen and Matt Korda, "Chinese nuclear forces, 2019," *Bulletin of the Atomic Scientists*, Vol. 75, No. 4, June 28, 2019. https://www.tandfonline.com/doi/pdf/10.1080/00963402.2019.1628511?needAccess=true.

186. Glaser has calculated that an HEU fueled research reactor could produce about 0.5 grams of plutonium per megawatt-day of operation if it was irradiating natural uranium targets. A 100 MW reactor operating 300 days per year would produce 15 kilograms of plutonium per year. If lithium targets were substituted for uranium ones, then an equivalent amount of tritium would be produced instead, which is about 190 grams per year. See: Alexander Glaser, "On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels," *Science and Global Security*, Vol. 14, 2006, p. 20. http://scienceandglobalsecurity.org/archive/sgs14glaser.pdf.

187. Assumes a 40% fuel burnup.

188. This implies that when it produced tritium, the Chinese reactor at Jiuquan used some amount of enriched uranium fuel.

a reactor with a power level of about 250 MW. This reactor would also produce about 55 kilograms of weapon-grade plutonium per year in addition to the tritium.[189] Over the last 34 years this would amount to about 1.9 metric tons of weapon-grade plutonium. Using higher fuel enrichments would reduce the required reactor power level and the amount of plutonium produced.

It is not that important how much weapon-grade plutonium China's tritium production reactor produces, since once one concludes that China is operating an undetected tritium production reactor, there is nothing to prevent China from operating an undetected weapon-grade plutonium production reactor as well. Though most Western analysts have assumed that China has stopped producing plutonium for weapons decades ago, China has never declared that it has ended fissile material production for weapons. Perhaps there is a reason for this omission.

Jeffrey Lewis of the Middlebury Institute of International Studies at Monterey has argued that China's nuclear arsenal is fissile material constrained and can be no more than "a few hundred such warheads."[190] Since China has been slowly expanding its nuclear stockpile, this constraint would provide some incentive for China to continue to expand its weapon-grade plutonium stockpile. A 100 MW natural uranium fueled plutonium production reactor would produce around 25 kilograms of plutonium per year. In 34 years this would amount to about 0.9 metric tons of plutonium. If the reactor had a 300 MW power level, the amount of plutonium would increase to 2.6 metric tons.

Whether China actually has such a plutonium production reactor today is unclear but these cases are just more examples of the uncertainty surrounding China's current weapon-grade plutonium stockpile. Due to this uncertainty, China could be easily have produced more plutonium than is often assumed. Therefore, my estimate of China's current weapon-grade plutonium stocks is 2 to 5 metric tons, which is the same as that of Wright and Gronlund. I also think it appropriate to use estimates rounded to the nearest whole ton rather than the 0.1 ton that several other analysts use, as this gives a better feel for the uncertainty of the estimates.

Potential for Future Growth to 2040

Given the uncertainty surrounding China's current stockpile of weapon-grade plutonium, it is not surprising that there is even more uncertainty regarding how much this stockpile might grow in the next 20 years. In addition to Zhang, Frank von Hippel and Masafumi Takubo of Princeton University have looked at this issue.[191]

Zhang as well as von Hippel and Takubo point out that if China starts operating the two breeder reactor prototypes (CFR-600s) that are under construction, then it could extract weapon-grade plutonium from these reactors' blankets.[192] Both sets of analysts base their calculations on the work of Glaser and Ramana, who calculated the weapon-grade plutonium production potential of India's Prototype Fast Breeder Re-

189. "Hanford Reactor and Separations Facility Advantages," HW-78100, Hanford Atomic Products Operation, Richland, Washington, June 27, 1963, p. 20. https://www.osti.gov/servlets/purl/10184818.
190. Jeffrey Lewis, *Paper Tigers: China's Nuclear Posture*, Adelphi Papers, 2014, p. 93. https://www.tandfonline.com/toc/tadl20/54/446.
191. Frank von Hippel and Masafumi Takubo, "Ending the separation of plutonium," Draft, July 10, 2020.
192. For von Hippel and Takubo see *ibid.*, p. 37. For Zhang see: Hui Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities," June 23, 2020, p. 33. http://npolicy.org/article_file/Hui_Zhang_Paper.pdf.

actor (PFBR).[193] Adjusting for the difference in reactor power level (the CFR-600 is 600 MWe and the PFBR is 500 MWe), then China's two breeder reactors would produce 347 kilograms of weapon-grade plutonium per year. Von Hippel and Takubo round this to 340 kilograms per year, Zhang to 400 kilograms per year. Both sets of analysts assume that since the early reactor cores would contain Russian-supplied uranium as fuel, there might be a peaceful use constraint on the plutonium produced. Therefore, China might not start using this weapon-grade plutonium in its weapon program until 2030, when it would start using its own plutonium fuel. Therefore, von Hippel and Takubo see the potential for the production of 3.4 metric tons of weapon-grade plutonium by 2040 and Zhang 4.0 metric tons.

Of course, the Chinese could start producing the weapon-grade plutonium as soon as the reactors start operating (currently scheduled for 2023 and 2026) and produce even more weapon-grade plutonium. On the other hand, the reactors' construction could be delayed and they may start operating much later. Or the reactors could operate poorly as many breeder reactor prototypes have done, and they might produce little or no weapon-grade plutonium. One intermediate possibility is that the Chinese would only extract the weapon-grade plutonium from the radial blanket, as the axial blanket might be processed with the core's spent fuel. Processing the radial blankets from both reactors would produce a total of 222 kilograms of weapon-grade plutonium each year. One advantage of using these breeder reactors to produce weapon-grade plutonium is that the plutonium is significantly more concentrated in the spent fuel than in light-water power reactor spent fuel. For example, the 222 kilograms of plutonium from the reactors' radial blankets would be contained in only 6.3 metric tons of spent fuel.

Von Hippel and Takubo also consider that China could produce weapon-grade plutonium in its CANDU 6 heavy water moderated power reactors. By irradiating the fuel to a burnup of 1,200 MWD/Te instead of the normal 7,000 MWD/Te, the plutonium so produced would be weapon-grade (6% Pu-240).[194] The CANDU 6's online fueling system would make this easy to accomplish. However, this could not be done for the entire reactor, since it would require using 5.8 times as much fuel per year and the reactor's refueling machine could not operate quickly enough. If this rapid refueling were limited to only one-eighth of the core, it would be feasible. Each reactor would then produce 67 kilograms of weapon-grade plutonium per year. The plutonium would be at a concentration of only 1 kilogram per metric ton, so reprocessing the low burnup fuel from both reactors would require 134 metric tons per year of reprocessing capacity. This would be a significant fraction of China's reprocessing capacity. Finally, as was noted by von Hippel and Takubo, China's peaceful use agreement with Canada for these reactors requires Canada's permission to carry out the reprocessing, which may deter China from taking this action.

China could also produce weapon-grade plutonium in its light-water power reactors. Some of these are of indigenous design and are not bound by any peaceful use agreements. However, producing low burnup spent fuel in these reactors is not as easy as in a CANDU 6 as the reactors would need to be shut down every 6 months for refueling. Using first startup cores at each refueling, a large reactor (1,000 MWe) would produce about 250 kilograms of weapon-grade plutonium per year.[195] This plutonium would be contained

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193. Alexander Glaser and M. V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science and Global Security*, Vol. 15, 2007. http://scienceandglobalsecurity.org/archive/sgs15glaser.pdf.
194. M. S. Milgram and K. N. Sly, "Tables of the Isotopic Composition of Transuranium Elements Produced in Canadian D_2O Moderated Reactors," AECL- 5904, Atomic Energy of Canada Limited, August 1977, p. 18. https://inis.iaea.org/collection/NCLCollectionStore/_Public/09/360/9360944.pdf.
195. Yashar Rahmani et al., "Calculation of the fuel composition and the thermo-neutronic parameters of the Bushehr's VVER-1000 reactor during the initial startup and the first cycle using the WIMSD5-B, CITATION-LDI2 and WERL codes," *Annals of Nuclear Energy*, Vol. 57, 2013, pp. 68-83. https://ac.els-cdn.com/S030645491200463X/1-s2.0-S030645491200463X-main.pdf?_tid=265afa87-895d-42db-b110-52cdbd488ddf&acdnat=1539107995_47ac68425544f3db1f9c01078a4fe753.

in about 141 metric tons of spent fuel. Given China's limited reprocessing capacity, not very many reactors could be operated in this manner but even just one reactor could produce 5 metric tons of weapon-grade plutonium between 2020 and 2040.

Neither von Hippel and Takubo nor Zhang consider the possibility that China may already have a dedicated plutonium production reactor in operation. Even if China does not currently have such a reactor, it could build one quickly since the reactor's low operating temperature and low fuel burnup make building such a reactor simpler than building a power reactor. Zhang claims that "it is unthinkable politically for China to resume plutonium production for weapons."[196] However, political circumstances can change rather quickly and it may not be as unthinkable as Zhang believes. As was discussed, it is likely that China is currently producing tritium for weapons in an undetected reactor. Unless this tritium production reactor uses HEU fuel, it will already be producing some weapon-grade plutonium as a by-product. A dedicated plutonium production reactor with a power level of 100 MW to 300 MW could produce 0.5 to 1.5 metric tons of weapon-grade plutonium respectively between 2020 and 2040.

In sum, there are various methods whereby China could produce up to 5 metric tons of additional weapon-grade plutonium between 2020 and 2040. On the other hand, perhaps Zhang is correct and China has no interest in producing any additional weapon-grade plutonium. Therefore, the range from 0 to 5 metric tons is a reasonable estimate of how much additional weapon-grade plutonium China might produce between 2020 and 2040.

Non-Weapon-Grade Plutonium[197]

Current Stockpile 2020

Some analysts estimate that China's current stockpile of non-weapon-grade plutonium is smaller than its stockpile of weapon-grade plutonium. Von Hippel and Takubo as well as Zhang note that China has reprocessed some light-water power reactor spent fuel at its pilot civilian reprocessing plant at Jiuquan.[198] This facility has a nominal capacity of 50 metric tons of spent fuel per year. It started operation in 2010 but for many years its performance was quite poor. Both Zhang and von Hippel and Takubo, considered it most likely that this plant has only reprocessed a total of 50 metric tons of spent fuel. This would produce about 0.5 metric tons of separated non-weapon-grade plutonium in total.

However, Albright notes that China's military plutonium production reactor at Guangyuan might have continued to operate until perhaps 2003 and could have produced non-weapon-grade plutonium after about 1991.[199] Albright estimates that the amount of this plutonium could be 1.4 metric tons with a range

196. Hui Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities," June 23, 2020, pp. 32-33. http://npolicy.org/article_file/Hui_Zhang_Paper.pdf.
197. This could include both fuel-grade and reactor-grade plutonium. The U.S. defines weapon-grade plutonium as having a Pu-240 content of less than 7%, fuel-grade plutonium as having a Pu-240 content of between 7% and less than 19% and reactor-grade plutonium as having a Pu-240 content of 19% or more. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, p. 17. https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf.
198. For von Hippel and Takubo see: Frank von Hippel and Masafumi Takubo, "Ending the separation of plutonium," Draft, July 10, 2020, p. 43. For Zhang see: Hui Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities," June 23, 2020, p. 22. http://npolicy.org/article_file/Hui_Zhang_Paper.pdf.
199. David Albright and Corey Hinderstein, "Chinese Military Plutonium and Highly Enriched Uranium Inventories," Institute for Science and International Security, June 30, 2005, p. 13. https://isis-online.org/uploads/isis-reports/documents/chinese_military_inventories.pdf.

0-2.6 metric tons. This reactor's metallic uranium fuel would have needed to be reprocessed soon after discharge, presumably at China's military reprocessing plant. Therefore, while 0.5 metric tons is probably the best estimate for China's stockpile of separated non-weapon-grade plutonium, China currently could have as much as approximately 3 metric tons.

Potential for future growth to 2040

Albright estimated that at the end of 2014, China already had 32.5 metric tons of plutonium contained in power reactor spent fuel.[200] Today this has grown to around 100 metric tons and by 2040 it will likely be in the range of 300-400 metric tons. China's stocks of separated non-weapon-grade plutonium will be determined by its more limited reprocessing capacity rather than the total amount of plutonium that its power reactors produce.

In addition to its 50 metric ton per year pilot reprocessing plant, China is building a 200 metric ton per year "demonstration" reprocessing plant which is to start operation in 2025. China is also negotiating with France for an 800 metric ton per year reprocessing plant. This plant is currently scheduled to start operation in 2030.

An upper limit on the amount of non-weapon-grade plutonium China might separate is to assume that all three plants operate at full capacity and start when they are scheduled. This would produce a total of 120 metric tons of separated plutonium by 2040. It is unlikely that such a large quantity will actually be produced.

Since 2007, China has considered building the large French reprocessing plant and it signed an industrial agreement with France in 2010. Despite signing additional agreements with France in 2013, 2014 and 2015, this project has yet to be finalized and there is a distinct possibility that the plant will never be built. In addition, the pilot reprocessing plant may well shut down once the 200 metric ton per year demonstration plant starts operating. Assuming that both the pilot and demonstration reprocessing plants operate at capacity and that the latter plant starts on time, then China would have separated about 33 metric tons of non-weapon-grade plutonium by 2040.

It is entirely possible that having reprocessed 50 metric tons of spent fuel, the pilot reprocessing plant has already been shut down. Further, the start of the demonstration reprocessing plant could be delayed to 2030 and even then, it may only operate at half capacity. Again, the large reprocessing plant from France may not ever be built. In this case China would only separate about 10 metric tons of non-weapon-grade plutonium by 2040.

This estimated range of 10-120 metric tons shows how uncertain China's future non-weapon grade plutonium holdings may be. A similar large range of estimates has been produced by other analysts. Zhang gives a range of 22-91 metric tons.[201] Von Hippel and Takubo give a range of 15-62 metric tons.[202]

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200. David Albright, Serena Kelleher-Vergantini, and Daniel Schnur, "Civil Plutonium Stocks Worldwide: End of 2014," Institute for Science and International Security, November 16, 2015. https://isis-online.org/uploads/isis-reports/documents/Civil_Plutonium_Stocks_Worldwide_November_16_2015_FINAL.pdf.

201. Hui Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities," June 23, 2020, p. 30. http://npolicy.org/article_file/Hui_Zhang_Paper.pdf.

202. For von Hippel and Takubo see: Frank von Hippel and Masafumi Takubo, "Ending the separation of plutonium," Draft, July 10, 2020, p. 53.

These estimates are for reactor-grade plutonium that would be produced in full-burnup fuel. However, every light-water reactor when it starts operating for the first time produces fuel-grade plutonium, which would be significantly easier to use in a nuclear weapon than reactor-grade plutonium.[203] For a 1,000 MWe reactor the first discharge spent fuel would contain about 90 kilograms of plutonium. Since China currently has in operation about 45,000 MW of light-water reactors, this means that about 4 metric tons of fuel-grade plutonium has already been produced. This plutonium is at a concentration of about 4 kilograms of plutonium per metric ton so that this plutonium would be contained in about 1,000 metric tons of light-water reactor spent fuel. If China's extensive plans to build additional nuclear power plants come to fruition, this number could grow to a total of more than 8 metric tons of fuel-grade plutonium by 2040. At 4 kilograms of plutonium per nuclear weapon, this would be 1,000 weapons worth in 2020 and 2,000 weapons worth in 2040.

Conclusions

There is substantial uncertainty as to how much weapon-grade plutonium China may have today. Not only is there uncertainty as to how well and how long China's two large graphite moderated plutonium production reactors operated but it is uncertain how much plutonium may have been produced in an undetected tritium production reactor. China may also be operating an undetected plutonium production reactor.

China's stocks of weapon-grade plutonium could grow significantly between 2020 and 2040. This plutonium could be produced in the blankets of breeder reactors, in China's commercial power reactors and in China's undetected tritium production reactor as well in a possible plutonium production reactor.

Up to now China has likely not separated much of the non-weapon-grade plutonium produced by its power reactors. However, it is building a demonstration reprocessing plant and could purchase a large reprocessing plant from France. If these plans come to fruition, then China's non-weapon-grade plutonium stockpile could become quite large. Some of this plutonium could be fuel-grade. Of course, these plans could run into technical or financial problems and not be nearly as successful as intended, which might greatly limit the size of China's non-weapon-grade plutonium stocks.

Table 3.01 gives a summary of this paper's estimates of both China's weapon-grade and non-weapon-grade separated plutonium stocks for 2020 and 2040. As has been stated in the text and is illustrated by the wide range of these estimates, there are substantial uncertainties.

203. Gregory S. Jones, "Iran's Bushehr Nuclear Power Reactor: A Potential Source of Plutonium for Nuclear Weapons," March 24, 2016. https://nebula.wsimg.com/0bde4bc34f1c736b5d635c12f23bec87?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.

Table 3.01: Estimates of China's Weapon-Grade and Non-Weapon-Grade Separated Plutonium Stocks 2020 and 2040

Plutonium Type	2020 Metric Tons	Increase from 2020 to 2040 Metric Tons	Total 2040 Metric Tons
Weapon-Grade	2-5	0-5	2-10
Non-Weapon-Grade	0.5-3*	10-120**	11-123***

*This could include several tons of fuel-grade plutonium.

**This could include at least 8 metric tons of fuel-grade plutonium from power reactor first discharge fuel.

***This could include about 10 metric tons of fuel-grade plutonium.

Chapter 4

Projecting Plutonium Stocks to 2040

Frank Von Hippel

At the end of the Cold War, Russia, the US and the UK declared some of their weapon plutonium and highly enriched uranium (HEU) excess and, along with France, announced that they were permanently halting production of HEU and plutonium for weapons.

Some of China's nuclear experts indicated privately that China had halted its production of highly-enriched uranium and plutonium for weapons and it is believed that China did end production by 1988.[204] Despite being pressed on the matter, however, China's government, has refused to join the other four permanent members of the UN Security Council in announcing a permanent halt.[205] Also, as far as is publicly known, India, Israel, Pakistan and North Korea continue to build up their stocks of weapons plutonium.

On the civilian side, China, France, India and Russia are still separating plutonium for use in power reactor fuel and Japan is planning to do so.

In this section, each of these countries' programs are discussed, and uncertainty ranges are projected for the possible sizes of their weapon and civilian plutonium stocks two decades hence, in 2040.

Weapon stocks.

In Figure 4.01, the global stock of weapon plutonium appears to level off after the end of the Cold War.

That reflects the 1994 Russian-US agreement to end producing plutonium for weapons in their huge production complexes.[206] Production continued on a smaller scale, however, in India, Israel, North Korea and Pakistan. Even though the impact of that production on global stocks is invisible on the scale used in Figure 4.01, it has been significant regionally.

Because of the dramatic reduction in their nuclear-warhead stocks since the end of the Cold War, Russia and the United States have large stocks of excess weapons plutonium and neither is expected to produce more for the foreseeable future. The question is how much of approximately 100 tons of weapons plutonium they have together declared excess they will actually eliminate within the foreseeable future. That is

204. Hui Zhang, *China's Fissile Material Production and Stockpile* (IPFM, 2017) http://fissilematerials.org/library/rr17.pdf.
205. See for example, the exchange between Chinese delegates to the UN Conference on Disarmament in Geneva on 8 August 2019, https://undocs.org/cd/PV.1515: At p. 23, A member of China's delegation, "In our view, a moratorium on production is not the fundamental path to completely and effectively resolving the FMCT issue." At p. 27: a member of the US delegation, "A moratorium … is a fundamental demonstrative trust-building measure that any State serious about negotiating an FMCT should, at a minimum, be able to support. China is the only nuclear-weapon State without such a moratorium."
206. Agreement Between the Government of The United States of America and the Government of the Russian Federation Concerning the Shutdown of Plutonium Production Reactors and the Cessation of Use of Newly Produced Plutonium for Nuclear Weapons," 23 June 1994.

considered below in the discussion of civilian stocks.

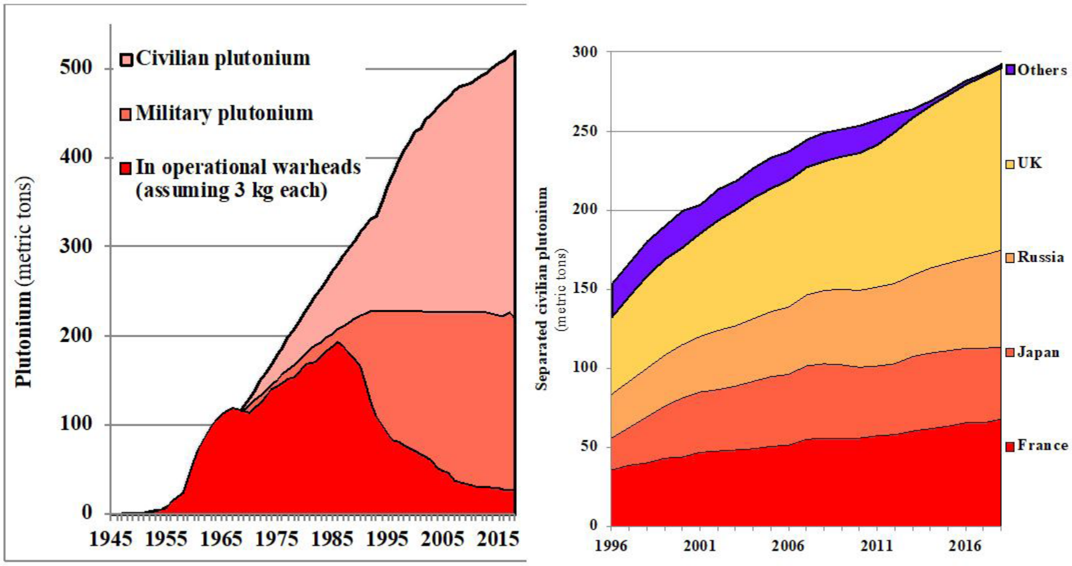

Figure 4.01: Growing stocks of unirradiated plutonium. Left. The total global stock of unirradiated plutonium. The stock of weapons plutonium plateaued with the end of the Cold War, after which the Soviet/Russian and US nuclear-weapon stockpiles plummeted, creating a plutonium disposal problem. Right. Despite the failure of breeder-reactor commercialization and excess stocks of Cold War weapons plutonium, the amount of unirradiated civilian plutonium continued to grow. Not shown are the stocks of China and India. China's was only 0.041 tons at the end of 2016 when it stopped reporting to the IAEA. India, which does not report its stocks publicly, considers most of the plutonium separated from the fuel of its heavy-water power reactors as "strategic," reserving the option to use it for nuclear weapons. As of the end of 2018, India's stock of civilian plus strategic unirradiated plutonium was estimated at between 3 and 11 tons (IPFM).

With regard to the remaining three of the first five nuclear-weapon states, China, France and the UK, China is the only one that might currently feel a need to increase its stock of weapons plutonium. This would be especially likely if China's worst-case analysts argue successfully that a US first strike on China's strategic nuclear missiles and of US ballistic missile defenses against those Chinese missiles that survive could effectively neutralize China's nuclear deterrent against US attack. Such worst-case analyses could give credibility to calls for more offensive warheads "just in case".[207]

Therefore, below, potential increases in weapon plutonium stocks are discussed for China, India, Israel, North Korea and Pakistan but no changes are projected in the weapon plutonium stocks of France, Russia, the United Kingdom and the United States. The UK and US have declared the sizes of those stocks. The IPFM estimated the sizes of the French and Russian stocks in 2010.[208]

The definition used for weapon-grade plutonium is plutonium that contains more than 90 percent Pu-239.

207. Hu Xijin, "China needs to increase its nuclear warheads to 1,000," editorial, *Global Times*, 8 May 2020, https://www.globaltimes.cn/content/1187766.shtml.
208. *Global Fissile Material Report 2010*.

China. China is estimated to have produced between 2.3 and 3.5 tons of weapon-grade plutonium.[209] That is enough for between 500 and 1000 warheads. China is estimated to have produced about 300 warheads.[210]

Technically, if China wished to produce more weapon-grade plutonium, it could use some of its power reactors, most easily, its two Canadian 2000-MWt (thermal) pressurized heavy-water reactors (PHWRs). The natural-uranium fuel in these reactors is in water channels similar to those in graphite-moderated power reactors designed to produce weapon-grade plutonium. Such channels can be opened without shutting down the reactor with fresh fuel added at one end of a channel pushing out irradiated fuel at the other. Ordinarily, fuel is not discharged until it reaches a burnup of about 7 MWt-days per kilogram of uranium. If discharged at 1 MWt-day/kgU, however, the plutonium it contains will be weapon-grade.[211] Under China's agreement for peaceful nuclear cooperation with Canada, China must have Canada's agreement before it can reprocess the PHWR fuel. Canada, if it agreed, would likely require IAEA safeguards on the reprocessing and recovered plutonium.[212]

China also could produce weapon-grade uranium with some of its light-water power reactors. But would have fuel after six months instead of the six years that is typical today. Also the fuel would contain only one fifth as much plutonium per ton, so five times as much spent fuel would have to be reprocessed to recover a given amount of plutonium.[213] If China's demonstration reprocessing plant were used and operated at its design capacity of 200 tons of spent fuel per year, about 0.35 tons of plutonium could be recovered from such low burnup fuel per year. It is unlikely that China would use the reprocessing plant proposed to be provided by France for this purpose, but France should require that any plutonium separated in this plant be placed under IAEA safeguards.

The most unobtrusive way in which China could obtain weapon-grade plutonium would be by reprocessing the irradiated uranium "blankets" around the cores of the one or two 600-MWe fast-neutron breeder reactors (CFR-600s) China currently has under construction (Figure 4.02). Scaling from calculations for India's 500-MWe Prototype Fast Breeder Reactor,[214] two CFR-600s operating at a 75% capacity factor could produce about 0.34 tons of weapon-grade plutonium per year. The first CFR-600 is currently scheduled to be operational in 2023 and the second in 2026. The first CFR-600 is expected to be fueled with Russian HEU during the first seven years, which might inhibit China from using it to produce plutonium for weapons during that period.[215] Starting in 2030, however, the two reactors could increase China's stock of weapon-grade plutonium by up to 3.4 tons by 2040.

209. Hui Zhang, *China's Fissile Material Production and Stockpile*.

210. Hans M. Kristensen and Matt Korda, "Chinese nuclear forces, 2019," *Bulletin of the Atomic Scientists* 75(4) 2019, 171–178, https://doi.org/10.1080/00963402.2019.1628511.

211. *Global Fissile Material Report 2010* (IPFM, 2010) 155-160, http://fissilematerials.org/library/gfmr10.pdf

212. Private communication from a Canadian safeguards expert. There is, of course, the possibility that China might clandestinely reprocess some PHWR fuel.

213 *Verifying the Agreed Framework* (Stanford University and Livermore National Laboratory, 2001) Figure 4.8, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/VAF-June.pdf.

214. Alexander Glaser and M.V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor."

215. Hui Zhang, personal communication, April 2020.

Figure 4.02: China's 600-MWe breeder reactor power plant, the CFR-600, under construction near Xiapu, China. The outline of the top of the cylindrical reactor containment vessel is visible in the center of the building. There are four cranes on yellow towers around the outside of the building plus one based inside the containment. Cooling water pipes are also visible. To the west of this site, excavation is underway to prepare for construction of a second CFR-600.[216]

India. As of the end of 2018, India had produced an estimated 0.4 to 0.7 tons of weapon-grade plutonium.[217] This plutonium was produced by two research reactors.[218] The first, CIRUS (Canada-India Reactor-US) – so named to reflect the facts that Canada supplied the reactor and the US supplied its heavy water – had a thermal power of 40 MWt. CIRUS began operating in 1963 and produced the plutonium for India's 1974 nuclear test. It was shut down at the end of 2010 as part of India's 2005 deal with the United States that led to the lifting of the international sanctions on India's nuclear program triggered by its 1974 nuclear test. India's second dual-purpose plutonium-production and research reactor, Dhruva (100 MWt) went into operation in 1985 and would produce about 0.018 tons of weapon-grade plutonium per year at a capacity factor of 65 percent.[219] Assuming Dhruva continues operating through 2040 at this rate, it would add 0.4 tons of weapon-grade plutonium to India's stock.

India has been building a 500-MWe Prototype Fast Breeder Reactor (PFBR) since 2004 (Figure 4.03). Its operation has been delayed year by year and its estimated cost has doubled.[220] The most recent projected operating date is late 2021. India's Department of Atomic Energy envisages building two follow-on 500-

216. Zhang Hui, as quoted in Stephanie Cooke, "CNNC Embarks on Second CFR-600," *Nuclear Intelligence Weekly,* 22 May 2020, p. 3.
217. Moritz Kütt, Zia Mian and Pavel Podvig, "Global stocks and production of fissile materials, 2018," *Military Armaments and Expenditures, 2019*.
218. When a heavy-water reactor is started up, some of the first fuel discharged has a low burnup and therefore contains weapon-grade plutonium. An upper bound of about 95 kilograms on this source is estimated in IPFM, *Global Fissile Material Report 2010,* p. 119.
219. *Global Fissile Material Report 2010*, p. 119.
220. IPFM blog, "India's prototype breeder reactor is delayed again," 12 March 2020, http://fissilematerials.org/blog/2020/03/indias_prototype_breeder.html.

MWe Commercial Fast Breeder Reactors (CFBRs) on the same site after the PFBR goes into operation.[221]

India's absolute refusal to place its breeder program or the associated reprocessing program under international safeguards in its 2005 agreement on peaceful nuclear cooperation with the United States[222] has resulted in concerns that it might be planning to use its breeders to produce weapon-grade plutonium for its weapons program.[223] Glaser and Ramana have estimated that, operating at a 75-percent capacity factor, the PFBR could produce about 0.14 tons of weapon-grade plutonium per year in its blanket.[224] At half that capacity factor, the amount would be half as much. Assuming that the PFBR goes into operation in 2022 and that the two CFBRs go into operation in 2030, the three reactors could increase India's stock of weapons plutonium by 2.5 to 5 tons by 2040.

Figure 4.03: Reactor vessel for India's Prototype Fast Breeder Reactor being lowered into place. It is not necessary to pressurize the sodium to keep it liquid at the temperatures at which heat is transferred from the sodium to produce high-pressure steam for the plant's power turbines. The vessel holding the core of a breeder reactor can therefore be large in diameter and relatively thin. Here, the vessel is being emplaced inside a containment vessel in case the reactor vessel leaks.[225]

Israel. Estimates of the power of Israel's plutonium production reactor at Dimona in the Negev Desert range from 40 to 140 MWt, resulting in great uncertainty in estimates of Israel's stock of separated weapon-grade plutonium. A mid-range estimate of the annual production rate, made in 2010, was 0.018 tons per year at a power of 70 MWt.[226] In 2018, the stock was estimated as 0.8-1.05 tons.[227] At 0.018 tons/yr,

221. Saurav Jha, "Waiting for the Fast Breeder Reactor."
222. Indian Ministry of External Affairs, "Implementation of the India-United States Joint Statement of July 18, 2005: India's Separation Plan."
223. Z. Mian, A.H. Nayyar, R. Rajaraman, and M.V. Ramana, *Fissile Materials in South Asia: The Implications of the U.S.-India Nuclear Deal* (IPFM, 2006) http://fissilematerials.org/publications/2006/09/fissile_materials_in_south_asi.html.
224. Alexander Glaser and M.V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor."
225. "India's first indigenously developed fast breeder reactor at Kalpakkam may achieve criticality in 2019," *Hindustan Times*, 20 September 2018, https://www.hindustantimes.com/india-news/biz-dae-reactor-bcm8/story-653iEzGRSXhnq25L4h-joWL.html.
226. *Global Fissile Material Report 2010* (IPFM, 2010) 109-112.
227. Moritz Kütt, Zia Mian and Pavel Podvig, "Global stocks and production of fissile materials, 2018," *Military Armaments*

Israel's stock of weapon-grade plutonium would increase by 0.4 tons by 2040. At that point, the reactor would be 75 years old but Israel is believed to use the reactor to produce 12-year half-life tritium for its weapons and therefore will have to replenish the tritium indefinitely even if it has enough plutonium and is producing more only as a byproduct of tritium production.

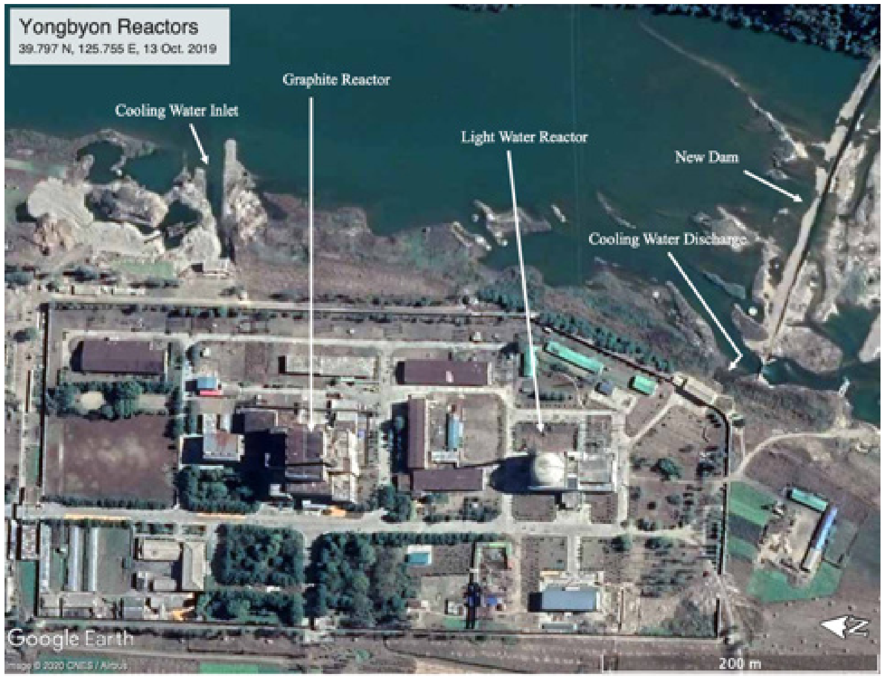

Figure 4.04: North Korea's two reactors in 2019. Left: the 20 MWt graphite-moderated, CO_2-cooled reactor built in the 1980s based on the published design of the UK's plutonium-production reactors. Right: the dome of the containment of the 100-MWt Experimental Light Water Reactor built starting in approximately 2010.

North Korea. To date, the Democratic People's Republic of Korea (DPRK) has produced all its plutonium with the ~20 MW-thermal (MWt) graphite-moderated, CO_2-cooled Yongbyon reactor (Figure 4.04). Operating at continuous full power, this reactor could produce about 6.7 kg of weapon-grade plutonium per year.[228] However, the reactor has been shut down for a significant fraction of the time since it began operating in 1986, and North Korea consumed plutonium in its six nuclear tests. Updating a 2017 estimate by Albright,[229] Kang and de Troullioud de Lanversin estimate that, as of the end of 2018, the DPRK had a remaining stock of 24-43 kg of separated plutonium.[230] Assuming a 50-percent capacity factor, the reactor could produce an additional 70 kg by 2040.

In addition, the DPRK has built – although, as of the end of 2019, it is not believed to have operated – an

and Expenditures, 2019.

228. The reactor core contains about 50 tons of natural uranium fuel, Jungmin Kang, "Using the Graphite Isotope Ratio Method to Verify the DPRK's Plutonium-Production Declaration," *Science & Global Security* 19 (2011) 121–129, Table 5, http://scienceandglobalsecurity.org/archive/sgs19kang.pdf.
At full power, the average incremental burnup of this fuel would only be about 150 MWt-days/tonU per year. An average discharge burnup of 300 MWt-days/tonU has been assumed.

229. David Albright, "North Korea's Nuclear Capabilities: A Fresh Look," ISIS, April 22, 2017, https://isis-online.org/uploads/isis-reports/documents/North_Korea_Talk_April_28_2017_Final.pdf.

230. Jungmin Kang and Julien de Troullioud de Lanversin, "North Korea," (IPFM, to be published).

Experimental Light Water Reactor (ELWR) with a thermal rating of approximately 100 MWt (Figure 4.04). The amount of low-enriched uranium (LEU) in the ELWR core is reportedly about 4 tons.[231] After 200 full-power days, the irradiated fuel would contain about 16 kilograms of weapon-grade plutonium.[232] Assuming 300 full-power days per year, the DPRK could use the ELWR to produce up to an additional half ton of weapon-grade plutonium by 2040.

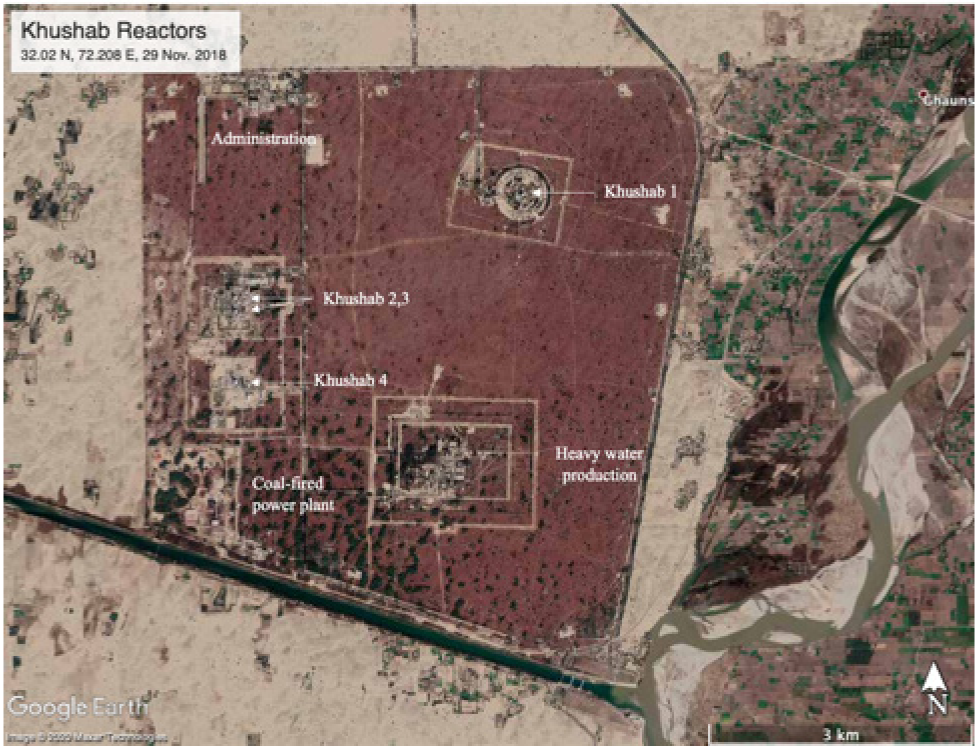

Figure 4.05: Each of Pakistan's four plutonium-production-reactors and the associated heavy-water production plant has its own rectangular inner security perimeter within a single complex at the junction of a large canal carrying water from the Indus to the Jhelum River. The small bare areas just inside the perimeter fence of the complex appear to be anti-aircraft missile sites.

Pakistan. After India's 1974 nuclear explosion, the US succeeded in persuading France to cancel the sale of a reprocessing plant to Pakistan. At the time, Pakistan had in any case only one power reactor, the 100-MWe Canada-provided Kanupp-1 heavy-water reactor, which was under IAEA safeguards. Pakistan's first-generation nuclear weapons therefore used HEU produced by gas centrifuges whose designs had been purloined from URENCO by A.Q. Khan. A weapon design was provided by China.[233]

In 1986-87, however, Pakistan began to build heavy-water-moderated plutonium production reactors in north-central Pakistan, 35 kilometers down the Jhelum River from the town of Khushab (Figure 4.05). Four production reactors were brought into operation in 1998, 2010, 2013 and 2015. The thermal powers of the first three reactor is estimated at about 40 MWt each with Khushab-4 estimated to have approxi-

231. Sigfried Hecker, "A Return Trip to North Korea's Yongbyon Nuclear Complex," November 20, 2010, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/HeckerYongbyon.pdf.
232. *Verifying the Agreed Framework,* Figure 4.8.
233. Jo Warrick and Peter Sievin, "Libyan arms designs traced back to China," *Washington Post*, 15 Feb. 2004, https://www.washingtonpost.com/archive/politics/2004/02/15/libyan-arms-designs-traced-back-to-china/2aacac24-4d49-4198-9aa0-7d68962fd8c2/.

mately twice that power, so a total of about 200 MWt.[234] As of the end of 2018, their cumulative output has been estimated as 0.2-0.4 tons of plutonium.[235] Assuming the reactors produce 0.8 grams of weapon-grade plutonium per MWt-day and operate 40-80% of the time, their combined annual output of weapon-grade plutonium would be 0.023-0.047 tons per year. They therefore could produce 0.5 to 1 tons of additional weapon-grade plutonium by 2040.

Other countries. It is possible that, in the next two decades, one or more additional countries might decide to separate plutonium for weapons.

The most recent proliferation crisis has focused on Iran, which, in addition to building a uranium enrichment program, built a research reactor near Arak, Markazi Province, quite similar to the CIRUS reactor that produced the plutonium with which India launched its nuclear-weapons program. In the 2015 Joint Comprehensive Plan of Action (JCPOA), Iran indicated, however, that unlike uranium enrichment, where it insisted on its rights, that it would work with international partners to redesign the reactor to produce an order of magnitude less plutonium; that it did not "intend…to engage in any spent fuel reprocessing" and that the spent fuel of the Arak reactor would "shipped out of Iran for the lifetime of the reactor."[236]

Also, as discussed in the next section on civilian plutonium programs, South Korea's Atomic Energy Research Institute has been campaigning for South Korea's "right" to reprocess like Japan. There is some basis for concern that one motivation for this campaign is an interest in having a nuclear-weapon option like Japan.[237]

Summary. Table 4.01 summarizes the conclusions of the discussion above. It will be seen that the most dramatic potential percentage increases in national stocks of weapons plutonium are in China, India, North Korea and Pakistan. Pakistan is and North Korea would be building up their stocks in the old-fashioned way, with dedicated production reactors. The scenarios for China and India are different, however. There, a new nightmare is being conjured: the dual use of nominally civilian plutonium breeder reactors to produce both power and weapon-grade plutonium.

234. David Albright, Sarah Burkhard, Claire Chopin, and Frank Pabian**, "**New Thermal Power Estimates of the Khushab Nuclear Reactors," 23 May 2018, https://isis-online.org/isis-reports/detail/new-thermal-power-estimates-of-the-khushab-nuclear-reactors/12.

235. Moritz Kütt, Zia Mian and Pavel Podvig, "Global stocks and production of fissile materials, 2018," *Military Armaments and Expenditures, 2019*.

236. Joint Comprehensive Plan of Action, 2015, Nuclear section, paras. 8 and 12, https://2009-2017.state.gov/documents/organization/245317.pdf.

237. Jungmin Kang and H.A. Feiveson, "South Korea's Shifting and Controversial Interest in Spent Fuel Reprocessing," *Nonproliferation Review*, Spring 2001, 70, https://www.nonproliferation.org/wp-content/uploads/npr/81kang.pdf.

Table 4.01: Declared or estimated national stocks of weapons plutonium in 2018 and projected ranges for 2040.

Country	**Stock of weapons plutonium** (metric tons)	
	2018[238]	**Range in 2040**
China	2.3-3.5	2.3 -7
France	5-7	5-7
India	0.4-0.7	0.6-6
Israel	0.8-1.1	0.8-1.5
North Korea	0.04	0.04-0.6
Pakistan	0.2-0.4	0.7-1.4
Russia	80-100	80-100
UK	3.2	3.2
US	38	38
Total	**130-154**	**131-165**

Civilian and excess weapon stocks

The countries with stocks of civilian and/or excess weapons plutonium are China, France, India, Japan, Russia, the United Kingdom and the United States. Their situations are discussed below. As a result of the 1997 Plutonium Management Guidelines, we have had since 1998 the benefit of annual public reports to the IAEA of their stocks of unirradiated civilian plutonium from all these countries except India.[239]

China. Although China – unlike France, Russia, the United Kingdom and the United States – has made no public statement to that effect, it is believed that, in 1987, China ended the separation of plutonium for weapons at both its production sites.[240]

China National Nuclear Corporation (CNNC) then decided to build a pilot civilian reprocessing plant with a planned throughput of 50 tons of light-water reactor spent fuel per year next to its shutdown Jiuquan military reprocessing plant.[241] Presumably, this was done to take advantage of the expertise at that site.

The pilot plant began operating in late 2010. At its planned throughput, it would have separated somewhat less than 500 kg of plutonium annually. During its first six years, however, it operated only briefly. In its first non-zero annual report to the IAEA under the Plutonium Management Guidelines, China reported 13.8 kg of separated civilian plutonium as of the end of 2010. This number did not change until the end of 2014, when China's report of the cumulative amount of civilian plutonium separated increased to 25.4 kg. At the end of 2016, the cumulative amount of plutonium separated increased again, to 40.9 kg.

238. From *Global Fissile Material* Report 2020.
239. IAEA, "Communication Received from Certain Member States Concerning Their Policies Regarding the Management of Plutonium," 1998.
240. Hui Zhang, *China's Fissile Material Production and Stockpile*.
241. The physical design capacity is 0.4 tons per day, corresponding to an annual capacity of almost 150 tons/year. The assumed average processing rate is therefore about one third of this theoretical design capacity (Zhang Hui, personal communication, April 2020).

Then China stopped reporting.[242] We have two differing unofficial reports on the plant's performance thereafter:

i) It began operating with an annual throughput of 50-60 tons per year in 2017 and 2018;

ii) CNNC completed reprocessing a cumulative total of 50 tons of spent fuel and decided to shut the pilot plant down and turn its attention to building the next plant.

In the second scenario, China's stock of civilian unirradiated plutonium would have increased to about 0.5 tons. If China's pilot reprocessing plant operated a design capacity from 2017 though 2040, it would increase China's stock of civilian plutonium by 12 tons.

The halt of China's reporting is of concern. As of mid 2020, China was the only country among the nine parties to the international Guidelines for the Management of Plutonium (Belgium, China, France, Germany, Japan, Russia, Switzerland, United Kingdom and United States) that had not reported to the IAEA on its stocks of unirradiated civilian plutonium as of the ends of 2017 and 2018. Requests for an explanation from Chinese experts have not been answered. The IAEA position is that it "does not request those Member States [that are parties to the Guidelines on the Management of Plutonium] to submit updates and has no role in connection with the implementation of these voluntary commitments."[243] The governments of other countries that have agreed to the guidelines could, however, ask China why it has not yet submitted reports on its stocks of civilian plutonium as of the end of 2017 and 2018. Arguably, France has a duty to do so because France is negotiating with China over the purchase of French reprocessing technology (see below).

In the meantime, 90 kilometers to the east of the Jiuquan pilot reprocessing plant, CNNC is building a "demonstration" reprocessing plant with a planned throughput of 200 tons of spent fuel per year.[244] The plan is to commission the plant in 2025.[245] If the plant were to operate at an average of 50 to 100 percent of its planned throughput thereafter, it could separate 15 to 30 tons of reactor-grade plutonium by 2040.

CNNC also continues negotiations, begun in 2007, with France's Orano over a joint venture to construct an 800 ton/yr reprocessing plant on China's coast. Since Orano reportedly has cut its asking price in half to €10 billion, the project is expected to move forward – if a site can be found.[246] In April 2018, Orano projected that, if the deal was finalized in 2018/19, the plant could be in operation "in the early 2030s." Given the continuing delay, the earliest date for operation can be assumed to have slipped to the mid-2030s. If that were achieved, then, assuming a linear ramp up to full capacity over 5 years, the plant could separate up to 20 tons of additional reactor-grade plutonium by 2040.

France. France's Orano today has only one foreign power reactor as a customer for its reprocessing services, a single small, old nuclear power plant in the Netherlands. Orano's reprocessing operation is therefore virtually entirely dependent upon Électricité de France's (EDF) nuclear power plants. Orano reprocesses about 1050 tons of EDF spent fuel annually and fabricates the recovered plutonium into mixed-oxide (MOX) fuel.[247] The operation also produces scrap MOX pellets, however, some of which

242. Last checked on 24 May 2020.

243. IAEA Press and Public Information e-mail to Frank von Hippel, 15 March 2019.

244. Hui Zhang, "Pinpointing China's new plutonium reprocessing plant," *Bulletin of the Atomic Scientists*.

245. *Ibid.*

246. The city of Lianyungang, a city in Jiangsu Province adjacent to one candidate site, rejected the plant in 2016, Chris Buckley, "Thousands in Eastern Chinese City Protest Nuclear Waste Project," *New York Times,* 8 August 2016, https://www.nytimes.com/2016/08/09/world/asia/china-nuclear-waste-protest-lianyungang.html.

247. *Traitement des combustibles uses provenant de l'étranger dans les installations d'Orano la Hague Rapport 2018* [*Treatment of spent fuel from abroad at Orano la Hague facilities Report 2018*]

Orano packages into fuel rods that are stored in the spent-fuel intake pools at La Hague along with such scrap from three decommissioned MOX fuel facilities in Belgium, Germany and France and the unused core of Germany's SNR-300 breeder reactor. The unused second core of France's *Superphénix* remains in that reactor's pool. As a result, France's national stock of unirradiated plutonium has increased steadily over 24 years by an average of 1.6 tons per year. Most of this increase has been reported in the category of "plutonium contained in unirradiated MOX fuel or other fabricated products at reactor sites or elsewhere" (Figure 4.06).

Since 2012, however, France's stock of fabricated MOX fuel has not increased but its stored plutonium oxide powder has, with the result that between 1995 and 2018, France's stock of unirradiated plutonium has continued to increase at an average rate of about 1.65 tons a year. A continuing accumulation at this rate would increase France's stock of civilian plutonium by roughly another 36 tons by 2040.

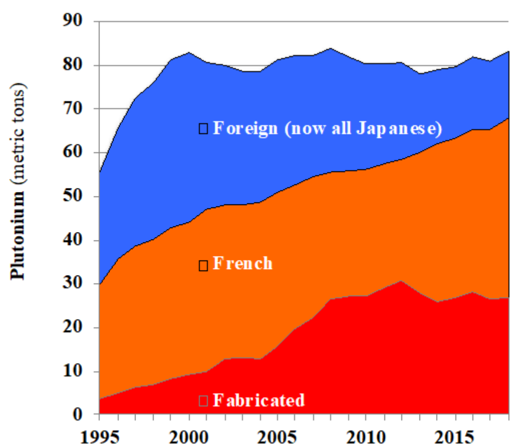

Figure 4.06: History and makeup of unirradiated plutonium in France. France's stock has increased at an average rate of 1.65 tons a year offsetting the reductions due to the non-renewal of foreign reprocessing contracts.[248] As of the end of 2018, all of the foreign unirradiated plutonium in France belonged to Japan. That plutonium is slowly being fabricated into MOX fuel and shipped back to Japan as the capacity to use it becomes available among the few Japanese reactors licensed to use MOX fuel.[249]

In an alternative scenario, France could follow its customers and decide to end reprocessing and then work down its own stock of almost 50 tons of already separated plutonium at La Hague, including the 15.5 tons belonging to Japan as of the end of 2018. This would leave for direct disposal at least 20 tons of unirradiated plutonium in unusable MOX fuel.

India. The only separated plutonium that India has that is clearly civilian is 0.4 tons derived from the reprocessing of fuel from India's Rajasthan 1 and 2 (RAP) reactors during 1982-86. Those two reactors

(Orano, 2019) p. 28, https://www.orano.group/docs/default-source/orano-doc/groupe/publications-reference/traitement-des-combustibles-uses-provenant-de-l-etranger-la-hague-2018.pdf?sfvrsn=6e75d797_4.

248. IAEA, "Communication[s] Received from Certain Member States Concerning Their Policies Regarding the Management of Plutonium."

249. In its annual declaration to the IAEA under the Plutonium Management Guidelines, France declared 15.5 tons of foreign plutonium as of the end of 2018, the same amount that Japan's Atomic Energy Commission declared was in France, JAEC, *Status Report of Plutonium Management in Japan – 2018*.

were built with Canadian assistance prior to India's nuclear test in 1974. Canada's agreement with India requires that the plutonium be kept under IAEA safeguards.

India's refusal to place under safeguards the plutonium separated from other heavy-water reactors is not necessarily a sign that it plans to use this plutonium in weapons.[250] An alternative explanation is that India is protecting its breeder program from IAEA safeguards. If it put any safeguarded plutonium into a breeder reactor core, the IAEA would demand that the reactor and any plutonium it produced be placed under safeguards as well.

For the purposes of this discussion, it will be assumed that plutonium separated from the spent fuel of India's heavy water reactors is to be used to provide startup fuel for breeder reactors.

India currently has three plants to reprocess power-reactor fuel, each with a design capacity to reprocess annually spent fuel originally containing 100 tons of uranium. The first of the twin PREFRE (Power Reactor Fuel Reprocessing) plants at Tarapur, north of Mumbai began processing power-reactor fuel in 1982 and PREFRE II in 2010. The Kalpakkam plant, located at the Madras Atomic Power plant, next to the site where India's breeder program is headquartered, began operations in 1998. A Fast Reactor Fuel Cycle Facility to reprocess the spent fuel from the Prototype Fast Breeder Reactor and commercial follow-on reactors is under construction.[251]

The operations of India's reprocessing plants have not been smooth. The plants have had prolonged shutdowns for repair and upgrades. Based on fragmentary information, the amount of plutonium they had separated as of 2018 is estimated to be between 3 and 11 tons.[252] This range corresponds to an average capacity factor for the reprocessing plants between 13 and 46 percent.[253] That would leave quite a bit of unsafeguarded plutonium in unreprocessed spent fuel. As of the end of 2018, India's unsafeguarded heavy-water reactors had produced 39 thermal TWt-days (1 TWt-day = 1,000 GWt-days). The associated spent fuel would contain about 21 tons of plutonium.[254]

In the past, DAE has floated plans for building additional reprocessing capacity[255] but there have been no public reports that these plans have been implemented. Assuming that the five unsafeguarded heavy-water power reactors under construction as of the end of 2018[256] come on line in 2020 and have an average capacity factor of 70 percent, and that no more are built, India's unsafeguarded heavy-water reactors could discharge spent fuel containing another 44 tons of plutonium by the end of 2037 (assuming three years of cooling before reprocessing).

If India built sufficient reprocessing capacity and that capacity operated well, it could separate cumulative-

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250. One of the test nuclear explosions that India conducted in 1998 reportedly did use reactor-grade plutonium, George Perkovich, *India's Nuclear Bomb* (University of California Press, 1999) 428.

251. World Nuclear Association, "Nuclear Power in India," https://www.world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx.

252. Including the 0.4 tons of IAEA-safeguarded plutonium from the Rajasthan 1 and 2 reactors which the DAE keeps in separate storage and does not intend to use in its breeder program, Moritz Kütt, Zia Mian and Pavel Podvig, "Global stocks and production of fissile materials, 2018," *Military Armaments and Expenditures, 2019*.

253. Operating at full capacity, the three reprocessing plants would have reprocessed 6300 tons of spent fuel. Assuming, 3.75 kilograms of plutonium per ton of spent fuel, the spent fuel would have contained about 24 tons of plutonium.

254. From the data on the IAEA's Power Reactor Information System, as of 2018, India's unsafeguarded heavy-water reactors (Madras 1&2; Kaiga 1,2,3&4; Tarapur 3&4) would have produced 38.72 TWt days. Assuming 0.007 TWt-days/ton, that would correspond to 5531 tons of spent fuel discharged. Assuming, 3.75 kilograms of plutonium per ton of spent fuel, the spent fuel would have contained about 21 tons of plutonium.

255. IPFM, *Plutonium Separation in Nuclear Power Programs* (2015) p. 56.

256. Kaiga 4 (came on line in 2019), Kakrapar 3&4 (began construction in 2010) and Rajasthan 7&8 (began construction in 2011).

ly up to 65 tons of plutonium by 2040. If it stayed with its current reprocessing capacity and that capacity continues to operate as poorly as it has historically, then the result would be a doubling of the estimated 3 to 11 tons of power-reactor plutonium separated as of 2018 to between 6 and 22 tons.

Ramana and Suchitra estimate that 5 tons plutonium will be required to fuel the Prototype Fast Breeder Reactor, including its first three annual reloads – about 2 tons for the initial core and 1 ton annually thereafter.[257] If India builds the planned two commercial breeder reactors with basically the same design, the startup requirement of plutonium for all three reactors would be 15 tons. If, more realistically, five annual reloads would be required before India could reprocess the fuel and fabricate it into fresh MOX fuel, that requirement would increase to about 21 tons. Thus, if India actually built three breeder reactors by 2040 depending upon the operation of its reprocessing plants, it would have between a shortage of 15 tons and an excess of one ton of plutonium relative to requirements. In the most extreme case of shortage, it would only have enough plutonium to fuel one breeder reactor. On the other hand, at the high end of the projected range for the amount of plutonium India might separate by 2040, if it built only one breeder reactor, it could have a stock of up to 15 tons of extra separated plutonium as of 2040.

Japan. Japan has been slowly drawing down the plutonium stockpile it has in France (Figure 4.07). Its stock in the UK (21.8 tons as of the end of 2018[258]) is frozen because of the tacit policy, adopted after a public uproar around the world over a shipment of plutonium from France to Japan in 1992,[259] that henceforth plutonium would be shipped to Japan only in the form of MOX fuel.[260] The failure and termination of UK's MOX-fuel-production plant in 2011 then left Japan's plutonium in the UK marooned there.[261]

Japan and the UK have opened discussions on the management of Japan's plutonium in the UK including of the possibility that the UK could take title to the plutonium and dispose of it along with the UK's own, much larger stock of separated civilian plutonium.[262] Those discussions are proceeding slowly, if at all, however – perhaps in part because of the poor optics of Japan paying the UK to get rid of its separated plutonium at the same time Japan's government is pushing to start separating more in Japan at a cost of about ¥200 billion (~$2 billion) per year.[263]

257. M.V. Ramana and J.Y. Suchitra, "Slow and stunted: Plutonium accounting and the growth of fast breeder reactors in India," *Energy Policy* 37 (2009) 5028-36*,* https://doi.org/10.1016/j.enpol.2009.06.063.
258. Including "approximately 0.6 ton of plutonium … expected to be added to the stockpile in the future," *Status Report of Plutonium Management in Japan -2018*, p. 2, http://www.aec.go.jp/jicst/NC/iinkai/teirei/3-3set_20190730.pdf.
259. David Sanger, "Plutonium Cargo Arrives in Japan," *New York Times,* 5 January 1993, https://www.nytimes.com/1993/01/05/world/plutonium-cargo-arrives-in-japan.html.
260. World Nuclear Association, "Japanese Waste and MOX Shipments from Europe," March 2017, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/transport-of-nuclear-materials/japanese-waste-and-mox-shipments-from-europe.aspx.
261. Fiona Harvey, "Sellafield Mox nuclear fuel plant to close," *The Guardian,* 3 August 2011, https://www.theguardian.com/environment/2011/aug/03/sellafield-mox-plant-close.
262. Ministry of Foreign Affairs of Japan, "Seventh Annual Japan-UK Nuclear Dialogue," 25-26 October 2018, https://www.mofa.go.jp/files/000432421.pdf.
263. ¥7.46 trillion over the 40-year planned operational life of the Rokkasho Reprocessing Plant, Nuclear Reprocessing Organization of Japan, 2020, http://www.nuro.or.jp/pdf/20200623_3.pdf.

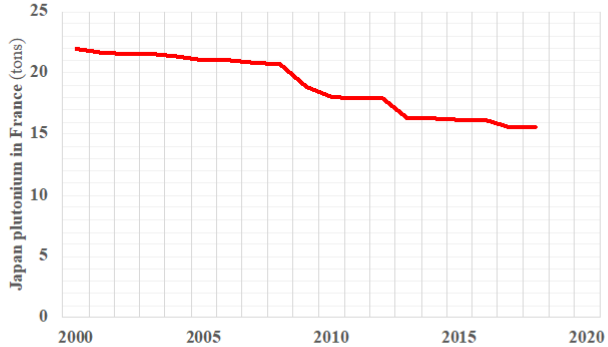

Figure 4.07: Japan's unirradiated plutonium in France is being gradually fabricated into MOX fuel and shipped to Japan as fast as it can be used. The average rate for the period shown is one third of a ton per year.[264]

Table 4.02 shows the makeup of Japan's stock of plutonium in Japan as of the end of 2018.

Table 4.02: Forms and locations of the approximately 9 tons of unirradiated plutonium in Japan as of the end of 2018 (metric tons).[265]

	Pu oxide and nitrate (tons)	In partially fabricated MOX fuel (tons)	In fuel (tons)
In R&D facilities	2.75	0.91	0.98
At Rokkasho Reprocessing Plant	3.60	–	
At power reactors	–	–	0.78
Total	**6.35**	**0.91**	**1.76**

Japan's plutonium R&D complex is declining. The prototype breeder reactor, Monju, and the pilot reprocessing plant at the Japan Atomic Energy Agency's Fuel Cycle Engineering Center in Tokai, have been shut down and are being decommissioned. The experimental (140 MWt) fast-neutron reactor, "Joyo," has been shut down since 2007 by damage due to a refueling accident.[266] The pilot MOX fuel fabrication facility remains to support the MOX fuel fabrication facility being built next to the Rokkasho Reprocessing Plant and possibly to produce MOX fuel for Joyo, should it operate again.

Seventy percent of Japan's in-country plutonium is in the form of either oxide or nitrate form mixed with an equal amount of natural or depleted uranium. Reactor-grade plutonium contains 14 to 15 percent plutonium-241 when it is discharged from a reactor core. Pu-241 decays into americium-241with a 14-year

264. Japan Atomic Energy Commission (JAEC), [annual] *Status Report[s] of Plutonium Management in Japan*. Before 2010, only the quantities of fissile plutonium were reported. These have been multiplied by 1.5 to get an estimate of total plutonium.
265. JAEC, *Status Report of Plutonium Management in Japan – 2018*.
266. Japan Atomic Energy Commission, *Current status of experimental fast reactor "Joyo,"* undated, https://www.jaea.go.jp/04/o-arai/joyo/english/Restoration/1.Current%20Status.pdf.

half-life. Americium-241 has a 430-year half-life and emits gamma rays when it decays that create a radiation hazard for workers in MOX fuel fabrication plants. Because of the buildup of Am-241, France's MELOX plant, the world's only operating MOX fuel fabrication plant and the model for Japan's plant, only processes plutonium that has been separated within the past six years.[267] Assuming that the spent fuel cooled for ten years before reprocessing, that corresponds to about 2.3 percent Am-241 in plutonium from LWR fuel. Processing older plutonium into MOX fuel – specifically the 6.35 tons Japan has in oxide and nitrate form – therefore would require removing the americium first or dilution with recently separated plutonium. Removal of americium from plutonium is not a new problem. Several processes have been used.[268]

Japan Nuclear Fuel Limited (JNFL) has a MOX fuel fabrication plant, J-MOX, under construction, next to the Rokkasho Reprocessing Plant. JNFL, which is responsible for both facilities, claims that J-MOX's initial operating date will be one year after the operating date of the reprocessing plant. Currently, that would be in 2023.[269]

JNFL's plan for plutonium separation at Rokkasho is shown in Figure 4.08. It has changed only with regard to the startup year. There is to be a ramp-up period of four years. Thereafter, the plant would operate at its full design capacity reprocessing 800 tons of spent fuel and recovering about 7 tons of plutonium per year. If reprocessing began in 2022 and was carried out according to this plan, by 2040, approximately 125 tons of plutonium would have been recovered.

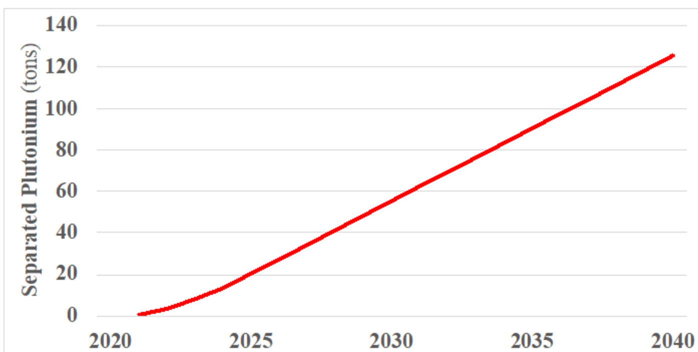

Figure 4.08: Japan Nuclear Fuel Limited's plan for plutonium separation at Rokkasho.[270] The plan is actually expressed in terms of tons of spent fuel reprocessed annually. Here, it has been assumed that 8.75 kilograms of plutonium would be separated from each ton of spent fuel.[271]

267. Y. K. Lee, J. C. Nimal, J. P. Degrange, and M. Chiron, 1994, "Radiation Shielding Calculation for the MOX Fuel Fabrication Plant MELOX," *Proc. of the 8th Int. Conf. on Radiation Shielding, Arlington, TX, USA, Apr. 24-28, 1994, Vol. 1*, pp. 336-343.

268. James D. Navratil and Wallace W. Schulz eds., *Transplutonium Elements—Production and Recovery* (American Chemical Society Symposium Series, 1981) https://pubs.acs.org/isbn/9780841206380.

269. World Nuclear News, "Further delay to completion of Rokkasho facilities," 28 December 2017, https://www.world-nuclear-news.org/WR-Further-delay-to-completion-of-Rokkasho-facilities-2812174.html.

270. 2021, 10 tons; 2022, 80 tons; 2023, 320 tons; 224, 480 tons; 2025, 640 tons; 2026 and thereafter, 800 tons, https://www.jnfl.co.jp/ja/release/press/2017/detail/file/20171222-1-1.pdf; https://mainichi.jp/articles/20190204/ddl/k02/020/087000c gives the startup as in Jan 2022 and reprocessing 80 tons in the Jan-Mar. period (both in Japanese).

271. JNFL recovered 3,604 kg of plutonium from the reprocessing of 425 tons of spent fuel at Rokkasho during 2006-2008, i.e. 8.5 kg/ton. (For plutonium recovered: JAEC, "Status Report of Plutonium Management in Japan – 2018;" for spent fuel reprocessed: JAEC, Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle, etc. Data Sheet 1, "Estimation of Nuclear Fuel Cycle Cost," 10 November 2011, slide 30, http://www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf.) For higher burnup and more recently discharged spent fuel, the amount of plutonium recovered would be somewhat larger.

Japan has six reactors that were licensed for MOX fuel before the Fukushima accident and that are either operating or being considered for relicensing after post-Fukushima upgrades. If these six reactors used the maximum amount of MOX fuel for which they are licensed, they could irradiate up to 60 tons of plutonium in MOX by 2040. If, in addition, the Ohma reactor, which is designed to be fueled entirely with MOX, were completed and came into operation in 2025, it could irradiate another 20 tons by 2040 (Figure 4.09).

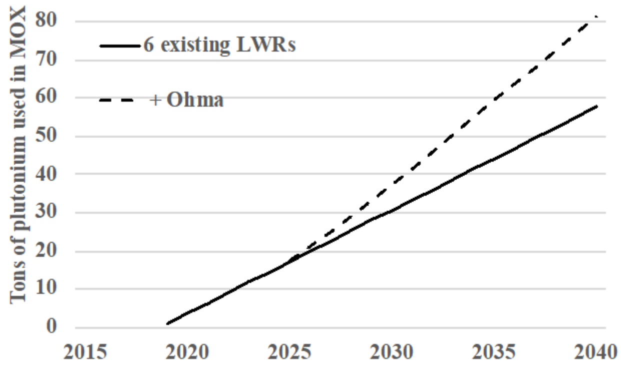

Figure 4.09: Two optimistic scenarios for Japan's irradiation of plutonium in MOX fuel. The six existing LWRs licensed for MOX fuel and likely to operate are Genkai-3, Ikata-3, Shimane-2, Takahama-3 and -4 and Tomari-3.[272]

In 2018, under pressure from the United States, Japan's Atomic Energy Commission (JAEC) announced that "Japan will reduce the size of its plutonium stockpile."[273] Even with the optimistic scenarios for Japan's plutonium use in MOX shown in Figure 4.09, however, that goal could not be achieved consistent with JNFL's operating plan. The 55-ton gap in 2040 could be partially offset if Japan agreed to accept the UK's offer to take title to the 22 tons of Japanese separated plutonium in the UK. Even so, JNFL would have to keep its rate of plutonium separation well below the design capacity of the Rokkasho Reprocessing Plant to live up to the JAEC's commitment.

The net result, however, would be to reduce the amount of unirradiated plutonium Japan owns in Europe in exchange for an increase of the amount of separated plutonium in Japan. A substantial increase in Japan would be consistent with JNFL's plan to have large "working stocks" of plutonium in its reprocessing and MOX-fuel-production complex. JNFL has built into the Rokkasho Reprocessing Plant a storage capacity for up to 30 tons of plutonium.[274] This is in line with the practice in France where, as of the end of 2018,

For spent fuel with a burnup of 43 MWt-days/kgU 10 years since discharge, for example, the amount recovered would be about 10 kg/ton if there were no process losses. For a burnup of 53 MWt-days/kgU the amount recovered would be about 11 kg/ton (*Plutonium Fuel: An Assessment,* OECD/NEA, 1989, Table 9, https://www.oecd-nea.org/ndd/reports/1989/nea6519-plutonium-fuel.pdf).

272. Masafumi Takubo and Frank von Hippel, An Alternative to the Continued Accumulation of Separated Plutonium in Japan: Dry Cask Storage of Spent Fuel," *Journal for Peace and Nuclear Disarmament*, 2019, https://doi.org/10.1080/25751654.2018.1527886.

273. Japan Atomic Energy Commission, "Basic Principles on Japan's Utilization of Plutonium," 31 July 2018, http://www.aec.go.jp/jicst/NC/iinkai/teirei/3-3set.pdf.

274. From JNFL's application document to Nuclear Regulation Authority dated March 8, 2018 https://www.nsr.go.jp/data/000264096.pdf, pp. 208-209 (in Japanese). Japan's separated plutonium is stored mixed with an equal amount of reprocessed uranium. This was a "fig-leaf" concession made to the United States in 1977 in exchange for the Carter administration's assent to Japan operating its pilot reprocessing plant at the Tokai-mura nuclear complex on the coast 120 km northeast of Tokyo.

47 tons of separated plutonium – almost five years of output – were stored at the reprocessing plant.[275] When it comes to plutonium inventory, France does not practice and JNFL does not seem to be planning a "just-in-time" supply chain such as that for which Japan's Toyota is justly famous.

Based on France's practice, JNFL's MOX fuel fabrication plant, which is under construction will have on the order of ten tons working stock of plutonium in process and in fabricated MOX fuel ready for shipment.

In an alternative, more responsible, scenario, Japan could decide not to operate the Rokkasho Reprocessing Plant until its MOX fuel fabrication plant is complete and has demonstrated that it is fully operable. This could be done using LEU if it was not possible to clean the americium-241 out of Japan's existing stock of separated plutonium to make it useable without dilution with fresh plutonium. Once the MOX plant had shown that it could in fact operate, the reprocessing plant and MOX plant operating on a just-in-time approach to minimize inventory would still probably have a combined working inventory of at least 10 tons of plutonium plus perhaps five tons of unusable MOX by 2040.[276]

A truly responsible policy would be for Japan to decommission the Rokkasho Reprocessing Plant and place its spent fuel in dry cask storage instead until a deep underground repository is built. That would remove large unnecessary burdens from both Japan's electricity rate payers and the global nonproliferation regime.

Russia. Russia is currently shifting its new BN-800 breeder reactor to MOX from mostly highly enriched uranium fuel. Operating at 80% capacity, the BN-800 would irradiate about 2 tons of plutonium annually, about as much plutonium as the Mayak reprocessing plant has been separating annually.[277] Rosatom plans, however, to expand the rate of plutonium separation at Mayak to its nominal design capacity of 4 tons per year, and build a 1500-ton per year spent fuel reprocessing plant in Zheleznogorsk.[278] If realized, these plans would increase plutonium separation in Russia to 18 tons per year by 2028.

These are decades-old plans, however, and there in no good reason to believe that Rosatom, focused as it is on profits, would commit the necessary funds to build a huge reprocessing plant at Zheleznogorsk at a time when Russia already has more separated plutonium than it knows what to do with.

For the purposes of projection to 2040, we assume a range of plutonium separation rates in Russia from zero increase to an increase of two tons per year in the 2020s and four tons per year in the 2030s for a resulting increase in Russia's stock of reactor-grade plutonium by 0 to 60 tons.

In addition to its civilian plutonium, Russia has 40 tons of excess weapon-grade plutonium: 34 tons of weapons plutonium declared excess under the Russia-US Plutonium Management and Disposition Agreement (PMDA) of 2000 and an additional 6 tons of weapon-grade plutonium produced after 1994 that Russia committed not to use for weapons the plutonium as a result of the Russian-US 1994 agreement to shut down their plutonium production reactors.[279]

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275. IAEA, INFCIRC/549/Add. 5/23.

276. Assuming that approximately 10% of the plutonium ends up in unusable MOX as in France.

277. Moritz Kütt, et al, "Plutonium Disposition in the BN-800 Fast Reactor".

278. IPFM, "Russia is expanding its reprocessing program at Mayak," 9 June 2016, http://fissilematerials.org/blog/2016/06/russia_is_expanding_its_r.html. For reprocessing plans at Zheleznogorsk, see World Nuclear Association, "Russia's Nuclear Fuel Cycle," 2020, https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-fuel-cycle.aspx.

279. *Global Fissile Material Report 2010*, p. 54. All the US plutonium production reactors had been shutdown by 1987 but Russia continued to operate two of its production reactors at Seversk until 2008 and one at Zheleznogorsk until because they were dual-purpose reactors, providing heat and electricity to those cities as well producing plutonium.

In the 2010 amendments to the PMDA, Russia committed to using the 34 tons of plutonium to fuel its BN-800 breeder reactor. In 2016, however, following the Obama Administration's unilateral decision to change the method of disposal of the US excess 34 tons from MOX fuel to dilution and deep burial, and in response to international sanctions on Russia because of its seizure of Crimea and, President Putin suspended Russia's participation in the PMDA. He made clear at the same time, however, that Russia would maintain its commitment not to use the 34 tons in weapons.[280] Reportedly, Russia is using reactor-grade instead of weapon-grade plutonium to fuel the BN-800.[281] Thus, it appears that Russia's excess weapon-grade plutonium will remain in storage for the foreseeable future.

United Kingdom. With the projected completion of the UK's reprocessing of legacy Magnox spent fuel in 2022, the UK's days of plutonium separation will be over. The question now is, how can the UK dispose of its stock of about 140 tons of separated plutonium, including the approximately 23 tons of Japanese and other foreign plutonium stranded in the UK?

The preference of the Nuclear Decommissioning Authority has been to contract with France's Orano to build a MOX fuel fabrication plant at Sellafield. The rationale is that MOX fuel fabrication is a "mature" technology. Also, the spent MOX fuel could be disposed with other spent LWR fuel. There would be no need to devise new storage and disposal arrangements for a new waste form.

Even though its sister company, Orano, could make many billions of dollars constructing a MOX fuel fabrication plant for the UK, however, Électricité de France, which owns the only LWR operating in the UK, and two additional LWRs under under construction there, has refused to use MOX fuel.

Two other reactor vendors, Atomic Energy of Canada Limited (AECL) and GE-Hitachi have offered to build dedicated nuclear reactors to irradiate the plutonium, but those proposals would require the government to finance the reactors as well as the associated fuel fabrication plants.

An additional complication in the case of GE-Hitachi is that the sodium-cooled reactors it proposes for plutonium disposal would use fuel containing sodium to conduct heat from the metal fuel "meat" to the cladding.[282]

This fuel design was used in the US Fermi I reactor (1966-72) and in the Experimental Breeder Reactor II (EBR II, 1965-94) on which the GE-Hitachi PRISM reactor is based. It is considered unsafe for disposal in an underground repository because the sodium in the fuel would react with water to generate hydrogen. The EBR II and Fermi I fuels are therefore being reprocessed into more stable waste forms at great cost at the US Idaho National Laboratory.[283] This makes the GE-Hitachi proposal absurd as a way to process the UK's plutonium into a stable waste form. In fact, GE-Hitachi is seeking the UK funding for entirely different purpose: to subsidize the construction of breeder reactors that would operate once-through initially but then recycle the plutonium in its spent fuel thereafter.

The UK is also developing a capability to immobilize in a stable insoluble waste form plutonium that

280. IPFM, "Russia suspends implementation of plutonium disposition agreement," 3 October 2016, http://fissilematerials.org/blog/2016/10/russia_suspends_implement.html.
281. IPFM, "Russia uses civilian reactor-grade plutonium to produce MOX fuel for BN-800," 29 August 2019, http://fissilematerials.org/blog/2019/08/russia_uses_civilian_reac.html.
282. The reason is that metal fuel, unlike oxide fuel swells and space must be left between the fuel and the cladding to accommodate that swelling.
283. Edwin Lyman, "External Assessment of the U.S. Sodium-Bonded Spent Fuel Treatment Program," International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development, 26–29 June 2017, Yekaterinburg, Russian Federation, https://s3.amazonaws.com/ucs-documents/nuclear-power/Pyroprocessing/IAEA-CN-245-492%2Blyman%2Bfinal.pdf.

would be difficult to clean up for use in fuel. It is recognized that immobilization could become an alternative for disposition of the UK's entire plutonium stock [284] but progress toward development of a UK deep underground national radioactive repository that could be used for direct disposal of immobilized plutonium is stalled. [285]

The current UK policy for plutonium is therefore one of secure interim storage

It is possible that a strategy for how to move forward with UK plutonium disposal could be decided by 2040 but it seems unlikely that a significant amount of plutonium could be disposed by then.

The UK's situation dramatizes the fact that, even after the huge cost of separating plutonium from spent fuel is incurred and the plutonium is fabricated into MOX fuel, the MOX fuel has a negative value. even for Électricité de France (EDF) which uses MOX fuel routinely in France and even for its EPRs, which are designed to be able take full cores of MOX fuel.[286] These reactors, which are rated at 1,630 MWe each, could each absorb annually two tons of plutonium in fresh fuel.[287] The fact that the UK government has provided EDF a huge subsidy to build two of these reactors on the Bristol Channel in southwest England[288] makes it even more remarkable that EDF has refused to use MOX fuel.

United States. In the Trump Administration's Department of Energy, the Assistant Secretary for Nuclear Energy, Rita Baranwal, has been expressing an interest in reprocessing US fuel in other countries and in encouraging the commercialization of sodium-cooled fast-neutron reactors.[289] But the she seems to be looking at the problem from the perspective of a nuclear engineer, i.e., that spent fuel contains both plutonium and U-238, which could be fissioned. She does not appear to have looked into the economics.

With regard to fast-neutron reactors, Baranwal seems to be representing the interests of the Idaho National Laboratory, the previous stop in her career trajectory. INL has been pushing for a larger version of Experimental Breeder Reactor II, which the Clinton Administration shut down in 1994 because its mission was obsolete. INL calls the proposed new $4+ billion reactor, the Versatile Test Reactor.[290] It is hard to take such proposals seriously. It is assumed here that they will not be carried through to completion.

In any case, the US has a plutonium disposal problem, not an unsatisfied demand for separated plutonium. In addition to the US commitment that it would dispose of 34 tons of excess weapon-grade plutonium in parallel with Russia, it has announced that it will dispose of an additional 16 tons or so of plutonium of different grades. The focus in the US is therefore on what to do with the approximately 50 tons of unir-

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284. UK Nuclear Decommissioning Authority, *Progress on Plutonium Consolidation, Storage and Disposition*, March 2019, https://www.gov.uk/government/publications/progress-on-plutonium-consolidation-storage-and-disposition.
285. Adam Vaughan, "Search restarts for area willing to host highly radioactive UK waste," *The Guardian,* 21 January 2018, https://www.theguardian.com/environment/2018/jan/21/search-area-willing-host-highly-radioactive-waste-uk-geology.
286. MOX-fueled LWRs require more control rods and have a narrower control margin than LEU-fueled LWRs. See e.g. *Status and Advances in MOX Fuel Technology* (IAEA, 2003) chapter 4, https://www-pub.iaea.org/MTCD/Publications/PDF/TRS415_web.pdf.
287. M. Arslan, I. Leboucher, E. Bouvier (AREVA) "Fuel cycle strategies to optimize the MOX in reactors," *Energy Procedia* 39 (2013) 59-68.
288. Holly Watt, "Hinkley Point: the 'dreadful deal' behind the world's most expensive power plant," *The Guardian*, 21 December 2017, https://www.theguardian.com/environment/2016/nov/29/french-nuclear-power-worst-situation-ever-former-edf-director.
289. Chris Schneidmiller, "DOE Nuclear Energy Chief Reaffirms Interest in Foreign Reprocessing for U.S. Spent Fuel," *Exchange Monitor,* 15 May 2020, https://www.exchangemonitor.com/doe-nuclear-energy-chief-reaffirms-interest-foreign-reprocessing-u-s-spent-fuel/?printmode=1.
290. Frank von Hippel and Edwin Lyman, "No Need for DOE's Costly 'Versatile Test Reactor'," *Nuclear Intelligence Weekly,* 7 February 2020, http://fissilematerials.org/library/fvh20.pdf.

radiated plutonium that has been declared "excess to national security needs."[291]

In the 2010 amendments to its Plutonium Management and Disposition Agreement (PMDA) with Russia, the US committed to dispose of the 34 tons of its excess weapon-grade plutonium covered by the PMDA in mixed-oxide (MOX) fuel to be irradiated in US LWRs.[292] After huge cost-overruns, in the construction of its MOX Fuel Fabrication Plant and prolonged internal debate, however, the US government, abandoned the MOX project.[293] It is now pursuing a "dilute and dispose" strategy in which plutonium-oxide powder is to be diluted with a classified material from which it would be difficult to separate. The mix is to be placed inside containers, centered inside large barrels for protection and to assure against criticality, in the Department of Energy's Waste Isolation Pilot Plant (WIPP), a deep repository in a salt bed in southeast New Mexico.

The US government tried to consult with the Russian government on its change of plans but there was no interest on Russia's part in renegotiating the agreement. The US therefore settled for keeping the Russian government informed.

Throughout the negotiation of the original PMDA in the 1990s, Russia objected to direct disposal of plutonium. It insisted that the plutonium isotopics must be changed to non-weapon-grade by irradiation in a reactor to forestall re-extraction of the plutonium from the disposal form to build new warheads of the same design as those from which the plutonium was extracted. The furthest it would go in the original (2000) PMDA was to agree that 8.43 tons of the 34 tons of plutonium that was impure and had never been in nuclear-warhead pits could be directly disposed without irradiation.[294]

In contrast, the US was relatively unconcerned that Russia's government might convert its excess weapon-grade plutonium back into weapons. The US viewed separated plutonium, whether reactor grade or weapon-grade, as weapon-usable and was focused on putting the excess plutonium out of the reach of sub-national groups. It was therefore unenthusiastic about Russia using its excess plutonium for breeder reactor fuel if the plan was to reprocess that fuel to recover the plutonium for recycle. That was, in fact, Russia's plan, although Russia agreed that it would neither reprocess the irradiated BN-800 fuel nor separate the weapon-grade plutonium produced in the radial blanket of the BN-800[295] until all the 34 tons on weapon-grade plutonium had been irradiated.[296]

There are many uncertainties in the US dilute and dispose plan, including where to site capacity to turn the plutonium metal in excess weapon "pits" into oxide[297] and the regulatory analyses and permissions

291. IAEA, "Communication Received from the United States of America Concerning its Policies Regarding the Management of Plutonium," INFCIRC/549/Add.6/22, 11 October 2019, https://www.iaea.org/publications/documents/infcircs/communication-received-certain-member-states-concerning-their-policies-regarding-management-plutonium.
292. IPFM, "U.S.-Russian Plutonium Management and Disposition Agreement, 11 May 2010, http://fissilematerials.org/blog/2010/05/us-russian_plutonium_mana.html.
293. Scott Judy, "DOE Terminates MOX Contract, Likely Killing Controversial Project," *Engineering Record,* 15 October 2018, https://www.enr.com/articles/45529-doe-terminates-mox-contract-likely-killing-controversial-project.
294. "Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation," 2000, "Annex on Quantities, Forms, Locations, and Methods of Disposition," http://fissilematerials.org/library/PMDA2010.pdf.
295. Operated to achieve the minimum required plutonium isotopic change, the BN-800 would produce about 9% as much weapon-grade plutonium in its blankets as it irradiated in its core, Moritz Kütt, Friederike Frieß & Matthias Englert, "Plutonium Disposition in the BN-800 Fast Reactor: An Assessment of Plutonium Isotopics and Breeding," *Science & Global Security*, Vol. 22 (2014)188–208, Table 8, http://scienceandglobalsecurity.org/archive/sgs22kutt.pdf.
296. 2000 Plutonium Management and Disposition Agreement between Russia and the United States, as amended by the 2010 Protocol, Article VI.
297 *NNSA's Long-Term Plutonium Oxide Production Plans Are Uncertain* (2019).

required to establish that placing so much plutonium in WIPP would be safe and politically acceptable to the New Mexico state government.[298]

In the short term, the US Department of Energy appears to have a path forward to dilute and dispose in WIPP up to 6 tons of plutonium not covered by the PMDA that is already in oxide form.[299] According to the Department of Energy's budget request to Congress for Fiscal Year 2021, three gloveboxes will be installed at the Savannah River Site that will in combination be able to blend down more than 1.5 tons of plutonium oxide per year starting in 2028.[300]

If the State of New Mexico and the US Environmental Protection Agency agree, absent other delays, it will take until 2049 to complete disposition of the 34 tons covered by the PMDA plus the 6 tons not covered by the agreement. The current projection is that up to 24 tons of plutonium could be diluted down by 2040 (Figure 4.10).

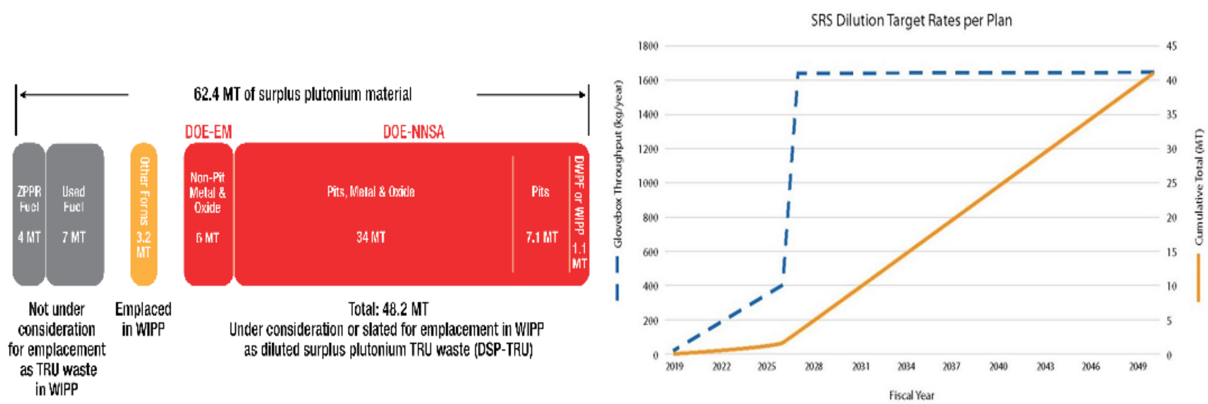

Figure 4.10: Plans for dilution of US surplus plutonium. Left: Of the 62.4 tons of US Government plutonium that has been declared excess to weapons use, 7 tons are in spent fuel, 3.2 tons already have been emplaced as plutonium waste in the Waste Isolation Pilot Plant (WIPP) repository and 4 tons are in fuel from a shutdown critical facility whose fate has yet to be decided. The current plan is to dilute the remaining 48.2 tons for disposal in WIPP. Right: Planned dilution capacity at DOE's Savannah River Site (SRS) and the cumulative amount of plutonium that could be diluted by 2050 if that capacity were fully used.[301] On this basis, approximately 25 tons would be disposed by 2040.

Other countries. The only country that is not currently reprocessing but is seriously interested in doing so is South Korea (ROK), whose Korea Atomic Energy Research Institute (KAERI) has been lobbying for decades for permission to reprocess.[302] South Korea's government has refused to give KAERI the go ahead, however, in the absence of US acquiescence in the two countries' Agreement on Cooperation on the Peaceful Use of Atomic Energy. The issue resulted in five years of negotiations on a renewal of that agree-

298.US Government Accountability Office, *Proposed Dilute and Dispose Approach Highlights Need for More Work at the Waste Isolation Pilot Plant* (2017).

299. US Department of Energy, "Surplus Plutonium Disposition," *Federal Register,* Vol. 81, No. 65, 5 April 2016, 19588, https://www.govinfo.gov/app/details/FR-2016-04-05/2016-07738.

300. Department of Energy, *FY 2021 Congressional Budget Request* (2020) Vol. 1, 661, 664.

301. *Review of the Department of Energy's Plans for Disposal of Surplus Plutonium in the Waste Isolation Pilot Plant* (National Academy Press, 2020) Figures 2-1 and 3.7, https://www.nap.edu/catalog/25593/review-of-the-department-of-energys-plans-for-disposal-of-surplus-plutonium-in-the-waste-isolation-pilot-plant.

302. "South Korea's Shifting and Controversial Interest in Spent Fuel Reprocessing."

ment in the course of which the two countries agreed to do a ten-year joint study on the "feasibility" of pyroprocessing, a type of reprocessing developed and declared to be "proliferation resistant" by Argonne National Laboratory, a claim that was assessed and rejected in 2009 by a joint study of experts from seven US national nuclear laboratories including Argonne.[303]

The joint ROK-US feasibility study is due to conclude in 2021. Before they were put on hold in 2010, KAERI's plans for pyroprocessing were quite ambitious. By 2016, it planned to have online an "engineering-scale" pyroprocessing facility with the capacity to reprocess 10 tons per year of light water reactor (LWR) spent fuel and, by 2025, a prototype facility with a capacity of 100 tons per year.[304] These capacities would be small relative to the approximately 500 tons of spent fuel that South Korea's LWRs discharge annually.[305] Ten or one hundred tons of LWR spent fuel contain, however, about one hundred or one thousand kilograms of plutonium, enough by the IAEA's metric to make about 12 or 125 nuclear warheads. If KAERI were given permission to proceed with these plans in 2021, but delayed by eleven years, then, by 2040, it could separate up to 0.6 tons of plutonium.

Summary. Table 4.03 summarizes the results of the above discussion. It will be seen that a dramatic reduction in global stocks of civilian and excess weapons plutonium by 2040 is not foreseen. Indeed, if the high end of the range were realized, the average annual growth in global civilian plutonium stocks would be about the same as that shown in figure 4.01 for 1996-2018 – almost 7 tons per year.

Table 4.03: National stocks of civilian and excess weapons plutonium in 2018 and projected to 2040.

Country	**Stock of civilian and excess weapons plutonium** (tons)	
	2018[306]	**Range in 2040**
China	0.04 (in 2016)	15-62
France	65.4	20-100
India	3-11	0-15
Japan	47.3	15-47.3
Russia	99	100-160
South Korea	0	0-0.6
UK	133.5	140
US	49.3	24-43
Total	**398-406**	**314-568**

303. R. Bari et al, *Proliferation Risk Reduction Study of Alternative Spent Fuel Processing* (Brookhaven National Laboratory, 2009), https://www.bnl.gov/isd/documents/70289.pdf.
304. Frank von Hippel, "South Korean reprocessing: An unnecessary threat to the nonproliferation regime," *Arms Control Today,* March 2010, https://www.armscontrol.org/act/2010_03/VonHippel.
305. IAEA, Power Reactor Information System for South Korea's LWR capacity in operation and under construction and assuming 20 tons of spent fuel discharged annually per GWe of generating capacity.
306. From *Global Fissile Material* Report 2020.

Chapter 5

Does China Need to Fuel its Power Reactors with Plutonium?

David Von Hippel

Executive Summary

After three decades of rapid economic growth, with attendant increases in energy use and in the environmental consequences of same, as of 2018 China arguably sits at a point of decision, inflection, or possibly both in the evolution of its electricity generation system, its nuclear power future, and possibly the future of its energy sector as a whole. As a source of electric power that is essentially free of the air pollutant and greenhouse gas emissions that plague the coal-fired generation that produces up about 70 percent of China's electricity, nuclear power has been touted as a solution to China's environmental challenges. Scenarios of nuclear power development in China, including those presented in this paper, span the range from modest growth to 80-100 GWe (gigawatts of electricity generation capacity) by 2050 (from about 34 GWe today) to growth to 300 to 400 or more GWe of nuclear power by 2050. China's nominal plans for its nuclear sector include the use of spent fuel reprocessing to extract plutonium (Pu), the use of mixed-oxide (MOx—a mixture of plutonium and uranium isotopes) nuclear fuel in light water reactors, and ultimately, the development and use of fast-breeder reactors that produce and use plutonium fuel. These technologies potentially pose risks for the international non-proliferation regime by creating large stocks and flows of plutonium that, if diverted, could be used in nuclear weapons or "dirty bombs". This paper explores the potential for China to meet its development needs and environmental goals through three alternative paths of nuclear power development through 2050, and explores the relative physical, economic, environmental, and socio-political consequences of the paths.

A comparison of alternative paths for the Chinese nuclear and electricity sectors—namely a "BAU" or Reference path reflecting recent trends and plans, a "MAX" path with fairly aggressive expansion of nuclear generation capacity, and a "MIN" path in which nuclear power capacity expands more slowly, and construction largely stops after 2040, with energy efficiency and renewable energy sources becoming a major focus—suggests that it will be possible to meet China's economic development, GHG and air pollutant emissions reduction, and other goals without an extended or massive build-out of LWR capacity, and without expansions of uranium enrichment or reprocessing capacity beyond projects now underway.

In particular, the "Minimum Nuclear" (MIN) path means that China will likely not become a major exporter of nuclear power technologies but will continue along its current trend of being perhaps a dominant provider of renewable power systems. In addition, the MIN path nuclear sector costs are much lower (both in aggregate and per unit output), than in the MAX and BAU paths. Although nuclear costs are only a small part of overall cost of providing energy services to the Chinese economy, past experience in China and elsewhere, as well as other studies of Chinese energy futures, have indicated that emphases on energy efficiency and renewable energy offers China the ability to effectively address environmental

concerns without significant (if any) additional costs, relative to a reference path. In addition, a path with less nuclear power, and fewer nuclear fuel supply and enrichment ("front-end") and nuclear spent fuel handling, transport, and reprocessing ("back-end") facilities is arguably easier to deploy in social and political terms, particularly if expectations for a stronger voice in how China's future unfolds continue to grow among the Chinese citizenry (although that is not a given as of this writing). The MIN path provides significant benefits over MAX/BAU paths in terms of Pu production and stocks, and thus offers a significantly lower risk of nuclear weapons proliferation than the other two paths.

In order for the MIN path (or a similar energy trajectory) to become reality in China, national policy support for energy efficiency and renewable energy will need to take precedence over policy support for nuclear power and technological and cost trends in energy efficiency and renewable energy will need to continue or accelerate. Trends in recent years have pointed toward the enhanced practicality of a low-nuclear path for the Chinese energy sector. These trends include a slow-down in reactor construction, and a re-thinking of nuclear safety regulations in the post-Fukushima era, ongoing structural change in the Chinese economy away from heavy industry, with attendant much-reduced growth in electricity needs, and exceedance of even the State's own ambitious targets for renewable energy.

The nations of the international community can help to influence a Chinese transition to a low-nuclear future through the acknowledgment of the benefits of a MIN path (or similar) for China by international political and trading partners, through international policies encouraging low-nuclear paths, and by embracing energy paths of their own that de-emphasize nuclear power, enrichment, and reprocessing, and encourage nuclear sector safety and transparency, would encourage China to move toward a low-nuclear future.

Acknowledgements

The author acknowledges and thanks the Nonproliferation Policy Education Center for its support for the development of this paper, and in particular thanks Henry Sokolski for his ideas in framing the paper and his review comments, and Stephen Thomas for his review of and additions to the paper.

Many of the energy security analytical frameworks and methods used to develop and evaluate the energy paths described in this report were assembled as a part of the Asian Energy Security and related projects carried out by the Nautilus Institute for Security and Sustainability over the last two decades, with funding from the MacArthur Foundation and other donors. The author is grateful to have had the opportunity to work extensively with colleagues from Nautilus and with many colleagues from East Asia in developing and applying these energy security approaches.

1 Introduction: China's Energy and Environmental Challenges

1.1 Projections of Economic Development and Energy Use in China, and Their Environmental Price

China's emergence as a global economic powerhouse from what was a largely rural and agrarian society even as of the 1980 has been a defining characteristic of the past few decades. The rate of growth in gross domestic product (GDP) in China exceeded 7 percent per annum in each year between 1991 and 2015, dipping only slightly below 7 percent in 2015 and 2016.[307] The result of this rapid growth has been that China's economy is more than 11 times larger today than it was in 1990, and nearly 30 times larger than it was in 1980. An increase in energy production and use, and especially electricity generation, has fueled the growth in China's economy. Primary energy use, a measure of all of the fuels that go into providing energy for an economy, has increased by nearly a factor of five since 1990, as has oil and oil products consumption, and electricity generation has grown nearly 10-fold in the same period. China edged the United States as the world's largest producer of coal in the mid-1980s. In 1990, coal production in China was over a billion tons (metric tons) per year, and rose to nearly 4 billion tons by 2013, before declining somewhat in recent years.

Although it has significant energy resources of its own, China has been obliged to turn to imports to help fuel its massive economic growth. China became a net importer of oil and oil products in the early 1990s, and a net importer of gas, as mostly as liquefied natural gas (LNG), in about 2006. By 2016, China was the world's third-largest importer of LNG, after Japan and the ROK. China's oil imports broke a monthly record early in 2017, with its imports exceeding those of the US to be the world's highest.[308] China sources its oil imports from a diverse array of nations; by 2014, 14 countries each supplied at least 2 percent of China's total oil imports, with Saudi Arabia its leading supplier at 16 percent.[309] China's energy imports dependency continues to increase, as consumption continues to rise while production of coal and oil, in particular, are relatively static. China's energy imports dependency is not yet, however, at the 90-plus percent level found in the ROK and Japan.

The large and rapid increase in China's energy use has been accompanied by a variety of environmental challenges. In 2006, China passed the United States to become the largest emitter of greenhouse gases (GHGs) among nations,[310] and by 2014 emitted 30 percent of global anthropogenic GHG emissions, although its per capita emissions remain less than those in the US and many other industrialized nations.[311] In addition, increased energy use in China has led to emissions of local and regional air pollutants high enough to be a significant danger to health much of the year in many Chinese cities, including Beijing,[312] and has contributed to water pollution, soil degradation, and numerous other environmental problems.

Although China has markedly improved energy use efficiency in recent years, particularly as measured in energy use per unit of GDP, shifting away from coal use to reduce global, regional, and local environmental problems has continued to be a priority in Chinese policy. This shift is to be in part accomplished by moving some of the most polluting industries out of the major southern and eastern Chinese cities to other areas of China, as well as moving some of those industries to other nations as the Chinese economy moves more toward high value-added manufacturing and services. In the electricity sector, this means a combination of improved efficiency in existing and new coal fired power plants and increasing the share

307.World Bank (2017), "GDP Growth, Annual (%)", graph and data available at http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=CN.

308. See, for example, Gordon Kristopher (2017), "China's Crude Oil Imports Hit a New Record Market Realist, April 19, 2017, available as http://marketrealist.com/2017/04/chinas-crude-oil-imports-hit-new-record/.

309. United States Department of Energy, Energy Information Administration (2015), *China*, last updated May 14, 2015, and available as https://energy.gov/sites/prod/files/2016/04/f30/China_International_Analysis_US.pdf.

310. See, for example, Carbon Brief, "Global Historical Emissions Map", available as https://www.carbonbrief.org/interactive-map-historical-emissions-around-the-world.

311. United States Environmental Protection Agency (USEPA, 2016), "Global Greenhouse Gas Emissions Data", available as https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.

312. See, for example, South China Morning Post (2017), "China orders cities to reduce emissions, as capital braces for another bout of heavy smog", dated February 13, 2017, and available as http://www.scmp.com/news/china/policies-politics/article/2070392/china-orders-cities-reduce-emissions-capital-braces.

of power generated from non-fossil resources, including renewable energy sources (particularly hydro-electric, wind, and solar power) and nuclear power.

China's nuclear sector is young by comparison to that of Japan and the ROK, but is and has been growing fast, as most of the reactors built worldwide at present are being built in China. With a large land area and a not-yet-powerful civil society sector, siting of nuclear plants and spent fuel facilities has not yet been a major problem for China, though it may grow to be so in the future.

1.2 Past and Projected Patterns of Growth of the Chinese Electricity Sector

Total electricity generation in China in 1990 was approximately 650 terawatt hours (TWh, or billion kilo-watt-hours), including Hong Kong, which is about the same as present-day Germany, with about 7 percent of China's population.[313] By 2016, electricity output and consumption in China had grown nearly 10-fold, supplanting the United States in 2011 as the nation with the largest electricity consumption (see Figure 5.01). Overall generation capacity grew even more rapidly, particularly in recent years, with growth in capacity averaging over 9 percent annually from 1990 through 2005, and 11 percent annually from 2005 through 2016 (see Figure 5.02).[314] Generation capacity in China now exceeds 1600 GW (gigawatts, or million kilowatts), nearly 60 percent more than the United States, where generation capacity stood at a bit over 1000 GW as of 2016.[315]

Thermal power, and specifically coal-fired power, has been the mainstay of Chinese electricity generation. Thermal power provided about 80 percent of generation in 1990, remaining near that level though 2010, falling only in recent years to under 72 percent by 2016. Despite rapid growth in nuclear capacity, nuclear power accounted for only 3.6 percent of electricity output by 2016, somewhat less than wind power in that year. Construction of hydroelectric capacity has been rapid in the past decade, and continues today with, nearly 12 GWe of capacity added in 2016 alone to a total of 330 GWe (of which about 27 GWe are pumped-storage plants used for peak power provision).[316] Electricity consumption in China has been dominated by the industrial sector, which consumed nearly 77 percent of power in 1990. The importance of the industrial sector has waned somewhat—to about 70 percent of total consumption in 2014, as residential and commercial/services electricity use has grown—but still remains the major user of electricity in the Chinese economy.

313. British Petroleum (2017), *BP Statistical Review of World Energy June 2017*, excel workbook accompanying volume available at http://www.bp.com/statisticalreview.
314. Some of the even more rapid growth in the post-2005 period was due to the addition of large amounts of wind and solar power generation capacity, which have lower capacity factors, and thus generate less energy annually per unit of capacity than, for example, coal-fired and nuclear power plants.
315. United States Department of Energy, Energy Information Administration (USDOE EIA, 2017), "Electricity in the United States", available as https://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states#tab2.
316. International Hydropower Association (2017), "China", last updated May, 2017, and available as https://www.hydropower.org/country-profiles/china. This reference highlights the construction of the "Wudongde project on the Jinsha River in the south- west, which will provide 10.2 GW installed capacity when complete" in 2020, and will be the sixth-largest hydro plant in the world.

The rapid overall growth in electricity consumption in the last decade, however, masks much slower growth in recent years—just over 3 percent annually between 2013 and 2016, as shown in the last four bars of Figure 5.02—as the Chinese economy has slowed somewhat, and greater emphases have been placed on improvements in energy efficiency, development of the services sector, and the reduction of heavy industry.

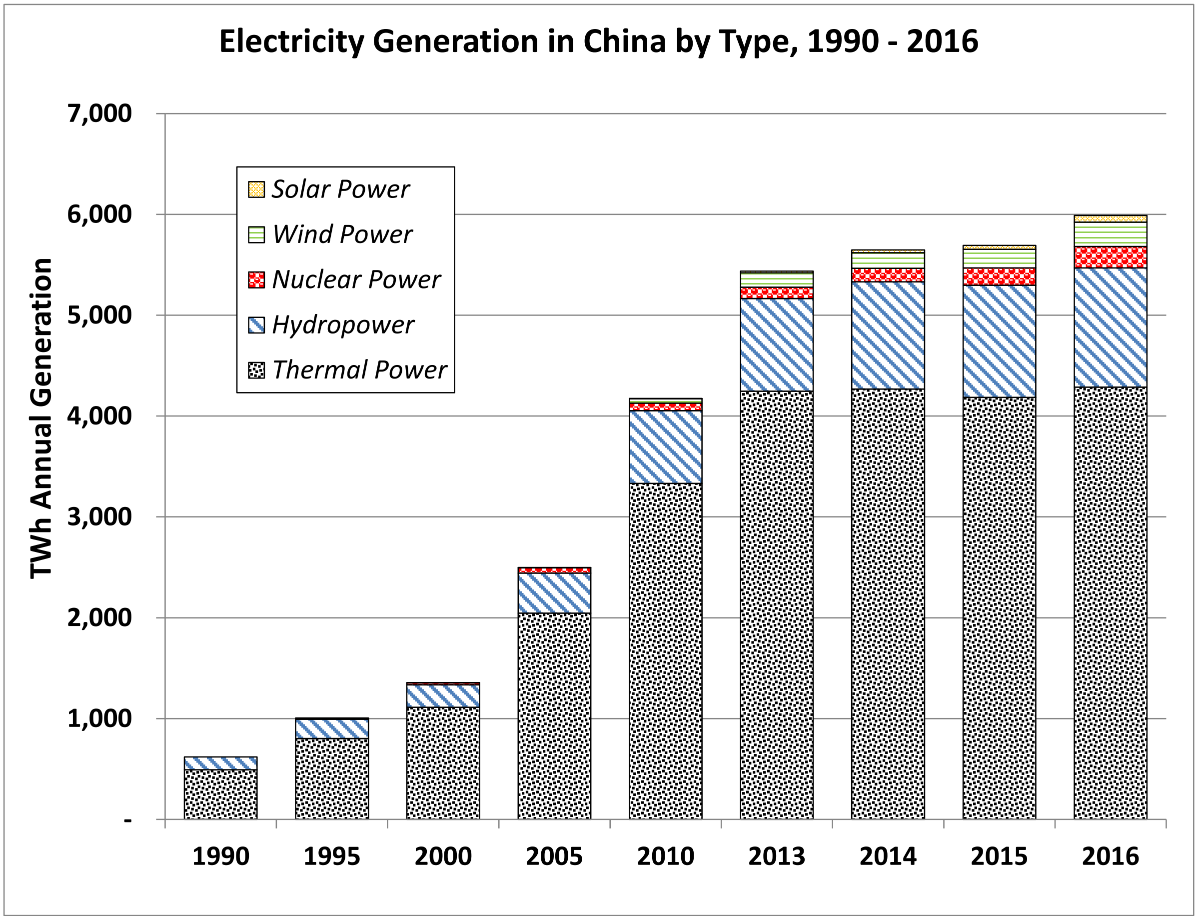

Figure 5.01: Electricity Generation in China by Type, 1990 through 2016[317]

317. Sources: Figures through 2014 from *China Statistical Yearbook, 2016*, available as http://www.stats.gov.cn/tjsj/ndsj/2016/indexeh.htm, with 2015 and 2016 data from John A. Mathews and Hao Tan (2017) "China's Continuing Green Shift in the Electric Power Sector: Evidence from 2016 data", *The Asia-Pacific Journal | Japan Focus*, Volume 15, Issue 10, Number 4, May 15, 2017, available as http://apjjf.org/-John-A--Mathews--Hao-Tan/5038/article.pdf.

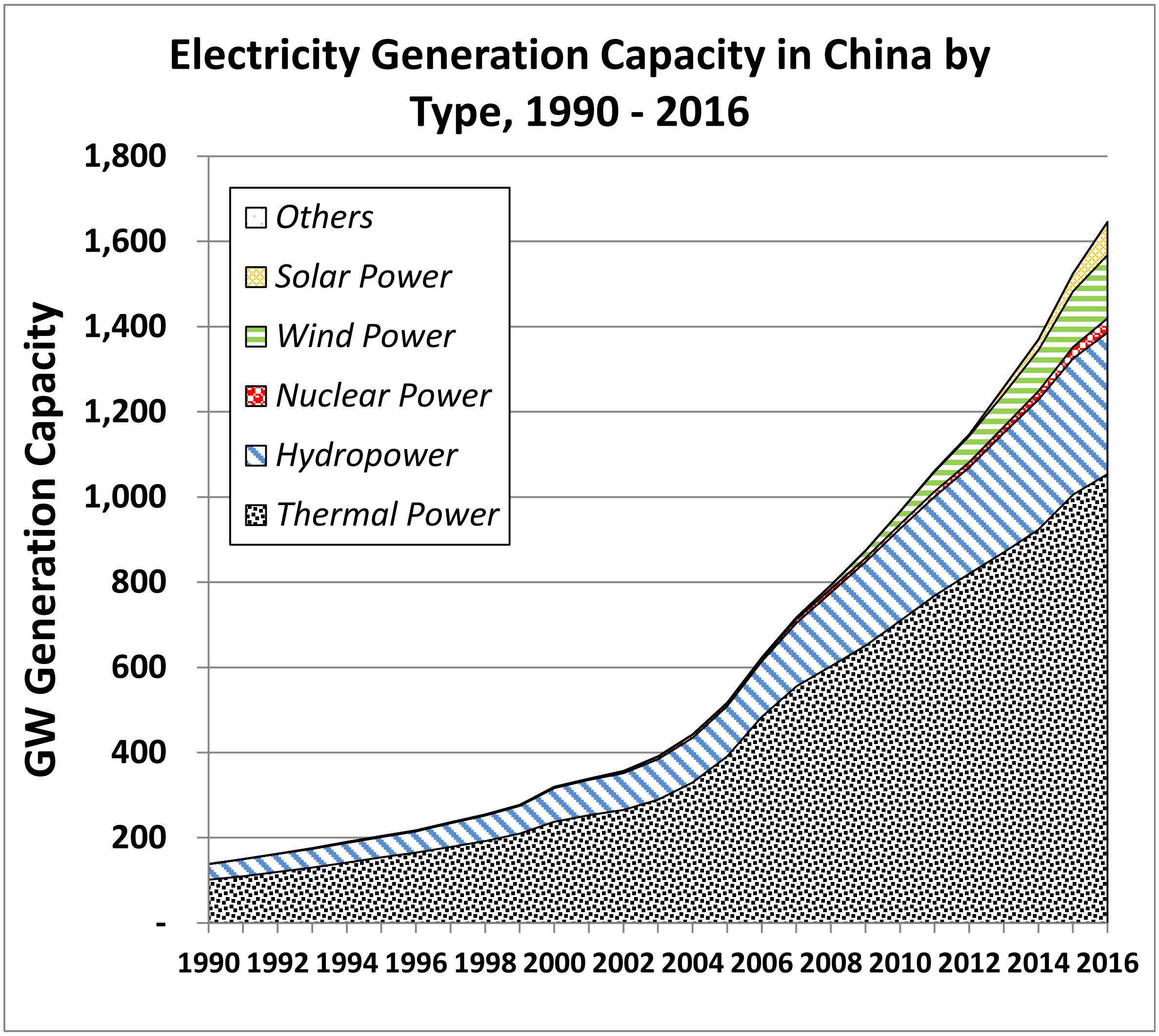

Figure 5.02: Electricity Generation Capacity in China by Type, 1900 through 2016[318]

Although electricity in the 1990s and 2000s was transmitted and distributed through mostly six regional grid "clusters", recent years have seen massive investments in transmission lines designed to tie the national grid together. In addition to several point-to-point UHV DC (Ultra-high voltage Direct Current) lines, China has invested and is investing tens of billions of dollars in UHV AC (alternating current) lines.[319] Together, these UHV DC and UHV AC lines are designed to move electricity from coal-fired, hydroelectric, and wind power plants in China's North and West to the major consuming cities in central and eastern China. An additional goal of these transmission projects is to reduce coal-fired power generation, with its attendant air pollution problems, in the vicinity of big coastal cities. China is reportedly investing hundreds of billions of dollars in total in electricity transmission and distribution between 2015 and 2020,

318. Sources of data are as indicated for Figure 5.01.

319. UHV DC lines are 800 kV (kilovolts) or more, and UHV AC lines are 1000 kV or more. By way of comparison, large high-voltage transmission lines in most countries are rated at about 500 kV. The higher the voltage, the more power can be carried by a given line. See, for example, *China Daily* (2014), "China Exclusive: China to build 12 power transmission lines", dated 2014-05-14, and available as http://shanxi.chinadaily.com.cn/2014-05/14/content_17505983.htm.

doubling the 2014 length of the lines in China's transmission system to over one million kilometers.[320] Nearly half of global additions to high-voltage transmission networks during 2014 through 2020 are expected to be in China.

Massive investments in manufacturing of electricity sector equipment in China have accompanied investments in transmission and distribution infrastructure, and have made China a world leader in the production of many types of power plants. China's largest wind turbine manufacturer, Goldwing, was third among global wind power firms in 2016, with an output of 6.4 GW (almost all installed in China), after leading the world the previous year.[321] China's solar photovoltaic (PV) firms produced 71 percent of the world's PV modules in 2016—and most of their modules were installed in China, as well as exporting panels to the rest of the world.[322] Almost by definition, China leads the world in production of coal-fired power plants, installed both in China and, increasingly, in other nations.[323] And China has slowly transitioned its nuclear industry from plants built with mostly foreign technology to plants designed and built in-country (see below).

The emphasis on manufacturing of renewable energy equipment has accompanied aggressive national goals for renewable energy deployment. Progress toward, and even past, these goals has been impressive. Deployment of solar photovoltaic power has been so rapid—topping 10 GW in a single recent month—that China's goal for solar deployment by 2020 under its 13th Five-Year Plan (FYP) has been nearly doubled, from 105 GW (already achieved) to 230 GW.[324] Progress toward wind power deployment goals has been nearly as impressive, with 129 GW of wind power capacity deployed by 2015, already over half of the 2020 target of 210 GW set in China's 13th FYP for energy. For some wind-rich provinces, wind and solar power already provided up to 15 percent of total generation by 2020.

China's renewable energy industries have not been without growing pains. Many wind generators, particularly in northern and western provinces, were built in anticipation of local electricity demand and/or construction of transmission facilities that have yet to catch up with wind power capacity, and as a result, wind energy output worth billions of dollars has been curtailed, far more than in other wind-rich areas of

320. See, for example, *Reuters* (2015), "UPDATE 1-China targets $300 bln power grid spend over 2015-20 – report", dated August 31, 201, and available as http://www.reuters.com/article/china-power-transmission-idUSL4N1171UP20150901, and Cision PR Newswire (2015), "Global Transmission and Distribution Market 2015 Report Says China Leading Power Transmission Line Additions to 2020", dated June 11, 2015, and available as http://www.prnewswire.com/news-releases/global-transmission-and-distribution-market-2015-report-says-china-leading-power-transmission-line-additions-to-2020-506906491.html. By way of comparison, the United States transmission grid includes about 700 thousand kilometers of high voltage lines (US Department of Energy (2014), "Top 9 Things You Didn't Know About America's Power Grid", dated November 20, 2014, and available as https://energy.gov/articles/top-9-things-you-didnt-know-about-americas-power-grid).
321. See, for example, Bloomberg New Energy Finance (2017), "Vestas reclaims top spot in annual ranking of wind turbine makers", dated February 22, 2017, and available as https://about.bnef.com/blog/vestas-reclaims-top-spot-annual-ranking-wind-turbine-makers/.
322. Jeffrey Ball, Dan Reicher, Xiaojing Sun, and Caitlin Pollock (2017), *The New Solar System: China's Evolving Solar Industry And Its Implications for Competitive Solar Power In the United States and the World*, Stanford University Steyer-Taylor Center for Energy Policy and Finance, dated March, 2017, and available as https://www-cdn.law.stanford.edu/wp-content/uploads/2017/03/2017-03-20-Stanford-China-Report.pdf.
323. See, for example, Hiroko Tabuchi (2017), "As Beijing Joins Climate Fight, Chinese Companies Build Coal Plants", *New York Times*, July 1, 2017, available as https://www.nytimes.com/2017/07/01/climate/china-energy-companies-coal-plants-climate-change.html?mcubz=0&_r=0.
324. See, for example, Joshua S Hill (2017), "China Continues Massive Solar Installations With 10.52 GW In July, Already Exceeds 2020 Target", Cleantechnica, dated August 22nd, 2017, and available as https://cleantechnica.com/2017/08/22/china-continues-massive-solar-installations-10-52-gw-july-already-exceeds-2020-target/; and Mark Osborne (2017), "China's solar boom to continue through 2020 as install targets revised", PVTech, dated July 28, 2017, and available as https://www.pv-tech.org/news/chinas-solar-boom-to-continue-through-2020-as-install-targets-revised.

the world (such as Texas). The transmission line projects described above are expected to significantly lower curtailment rates in coming years, allowing wind energy from the North and West of China to displace coal-fired power for the cities of the East and South.[325]

Accompanying this drive to use more renewable energy has been a drive toward energy efficiency in multiple sectors. China's National 13th FYP includes a reduction of 15 percent in energy use per unit of GDP relative to the level in 2015, and a reduction of 18 percent in carbon dioxide emissions per unit of GDP.[326] It should be noted that energy (and CO_2) per unit of GDP are indicators dependent on several factors, most notably, the composition of industry in China, the types of products produced, and the value of those products, as well as the actual energy efficiency per unit of physical output. CO_2 per unit of GDP additionally factors in the composition of the energy sources used by an economy. As a result, a reduction in energy use (and CO_2 emissions) per unit of GDP can be accomplished by a combination of true energy efficiency improvements, greater value added in products produced, offshoring of heavy (energy intensive/polluting) industries, and a shift toward production of more services, all of which are currently in play in China.

China's 13th Five-year Plan lays out a number of goals for electricity sector development by 2020 (see Table 5.01). These include overall electricity consumption (given as a range), development of various types of generation, and other parameters. Along with the aggressive targets for renewable power development described above, the 13th FYP shows growth in electricity generation/consumption, as well as generation capacity, slowing markedly relative to experience over the past decade.

Although longer-term official forecasts of electricity demand were not available for this paper, the trend of declining growth in Chinese electricity generation and consumption is echoed and extended in a number of forecasts by other analysts. For example, in the US Department of Energy's (US DOE's) *International Energy Outlook 2016*, the growth rate of electricity use in China progressively decreases from about 3.6 percent annually in 2015-2020 to 1.4 percent/yr in 2035 through 2040 (see Figure 5.03). As China's population growth will, based on the United Nations' "Medium Variant" estimate, have reached its peak just before 2030,[327] continued growth in electricity consumption late in the US DOE forecast means continued growth in electricity use per person. Overall, the USDOE forecast calls for average annual growth in electricity use of just under 2.5 percent from 2012 through 2040, resulting in a doubling of 2012 electricity use in China by 2040.

325. See, for example, Li Ying (2016), "Blowing in the wind", Chinadialogue, dated May, 31, 2016, and available as https://www.chinadialogue.net/article/show/single/en/8965-Blowing-in-the-wind.
326. Ma Tianjie (2017), "China's Ambitious New Clean Energy Targets", *The Diplomat*, dated January 14, 2017, and available as http://thediplomat.com/2017/01/chinas-ambitious-new-clean-energy-targets/.
327.Data downloaded from United Nations DESA, "World Population Prospects 2017", available from https://esa.un.org/unpd/wpp/Download/Standard/Population/.

Table 5.01: Thirteenth Five-Year Plan Main Objectives of Power Industry Development[328]

Category	2015 Value	2020 Target	Annual average Growth Rate [or change]
Installed Capacity (100 million kilowatts)	15.3	20	5.50%
West to East [Transmission Capacity] (100 million kilowatts)	1.4	2.7	14.04%
Total electricity consumption (trillion kilowatt hours)	5.69	6.8 - 7.2	3.6 - 4.8%
Electricity accounted for the proportion of terminal energy consumption	25.80%	27%	[1.2%]
Per capita installed capacity (kW / person)	1.11	1.4	4.75%
Per capita electricity consumption (kWh / person)	4142	4860 - 5140	3.2 - 4.4%
Non-fossil energy consumption share	12.00%	15%	[3%]
Non - fossil generation share of installed capacity	35.00%	39%	[4%]
Conventional hydropower (100 million kilowatts)	2.97	3.4	2.80%
Pumped Storage hydro (10 thousand kilowatts)	2303	4000	11.70%
Nuclear power (100 million kilowatts)	0.27	0.58	16.50%
Wind power (100 million kilowatts)	1.31	2.1	9.90%
Solar power (100 million kilowatts)	0.42	1.1	21.20%
Fossil energy power generation installed proportion	65%	61%	[-4%]
Proportion of installed capacity as coal-fired power	59%	55%	[-4%]
Coal-fired generation capacity (hundred million kilowatts)	9	<11	4.10%
Gas-fired generation capacity (hundred million kilowatts)	0.66	1.1	10.80%
Average coal consumption of new coal-fired units (grams of standard coal / kWh)		300	
Average coal consumption of active coal-fired units (grams of standard coal / kWh)	318	310	[-8]
Transmission Line Loss Rate	6.64%	<6.5%	
Charging Facilities Construction	Meet requirements for charging 5 million electric cars		
Electricity from Alternative Sources (100 million kWh) [Presumably for Transport]		4500	

328. Rough translation of "Box 2" from [China] National Development and Reform Commission, National Energy Board, *The Thirteenth Five-Year Plan for Electricity Development (2016-2020)*, available as http://www.ndrc.gov.cn/zcfb/zcfbgh-wb/201612/P020161222570036010274.pdf.

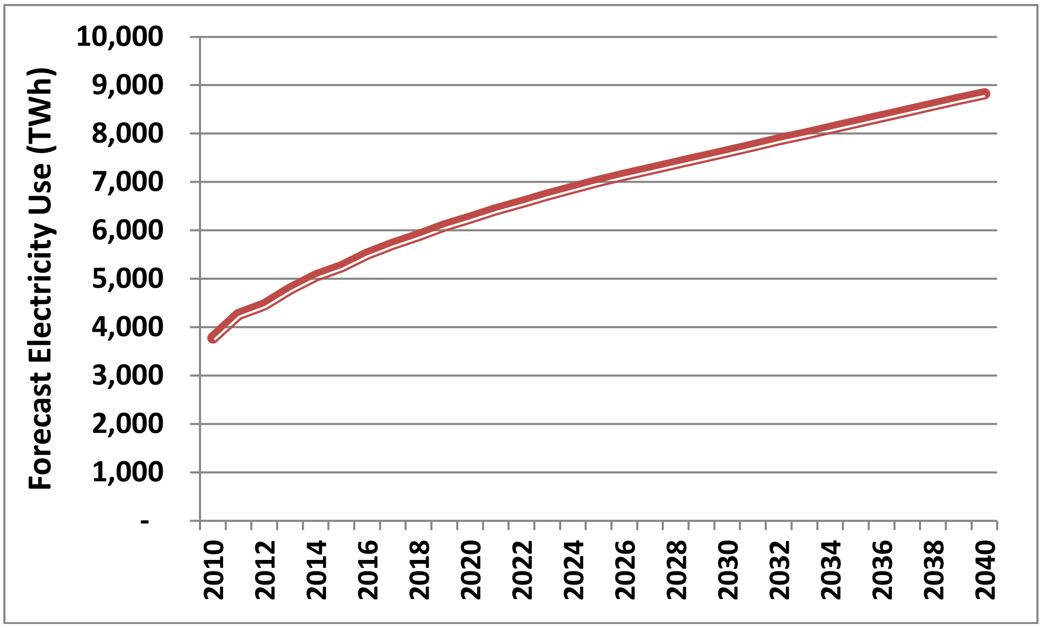

Figure 5.03: Forecast for Electricity Use in China, 2010-2040 (US Department of Energy International Energy Outlook)[329]

The current setting for China's nuclear power sector is thus characterized by rapid (by the standards of most countries) but slowing economic growth, increasing energy efficiency, and substantial progress on many development goals. In combination, these factors are resulting in demand for electric power that will continue to grow, but at progressively lower rates as the decades pass. At the same time, an aggressive drive to use electricity from renewable sources and reduce electricity generation (and its attendant environmental emissions) from coal creates a significant drive toward nuclear power as carbon- and air pollutant-emissions-free electricity source, but also significant competition for nuclear power among low-emissions electricity options.

1.3 China's Current and Planned Nuclear Sector: 1990s through 2040

Though the decision to develop civilian nuclear energy in China dates back to the 1970s, concrete efforts to construct nuclear power plants began only in the late 1980s. China's civilian nuclear power development began with the construction of the French-built reactors at Daya Bay, near Guangzhou, and providing power to Hong Kong and other cities in the region. This pair of 944 MWe reactors were constructed starting in 1987, and began operation in 1994. At about the same time, the smaller (298 MWe) Qinshan-1 unit was built with a combination of imported and domestic technology. These three reactors constituted the "first wave" of reactor construction in China, as described by the World Nuclear Association (see Fig-

329. Figure prepared using data from US Department of Energy's Energy Information Administration (2016), detailed tables for *International Energy Outlook 2016*, "Table: Delivered energy consumption by end-use sector and fuel; Case: Reference case | Region: China", available from https://www.eia.gov/outlooks/aeo/data/browser/#/?id=15-IEO2016&region=4-12&cases=Reference&start=2010&end=2040&f=A&linechart=Reference-d021916a.2-15-IEO2016.4-12&map=&sourcekey=0.

ure 5.04).[330] A second wave of reactor construction began in the late 1990s, and included four additional reactors at Qinshan, near Shanghai, this time in the 600 MWe class, and produced as stepping stones to development of a "Chinese standard" 1000 MWe-class unit, the CNP-1000. Two additional units at the Ling Ao power plant, very close to the original Daya Bay reactors. Like the Daya Bay plant, the Ling Ao reactors are based on French technology. A pair of reactors in northern Jiangsu province, between Shanghai and Beijing, the first set of Tianwan units, were built using Russian reactor technology but with control equipment supplied by an international consortium. These first two Tianwan units were completed as the third wave of reactor construction began.

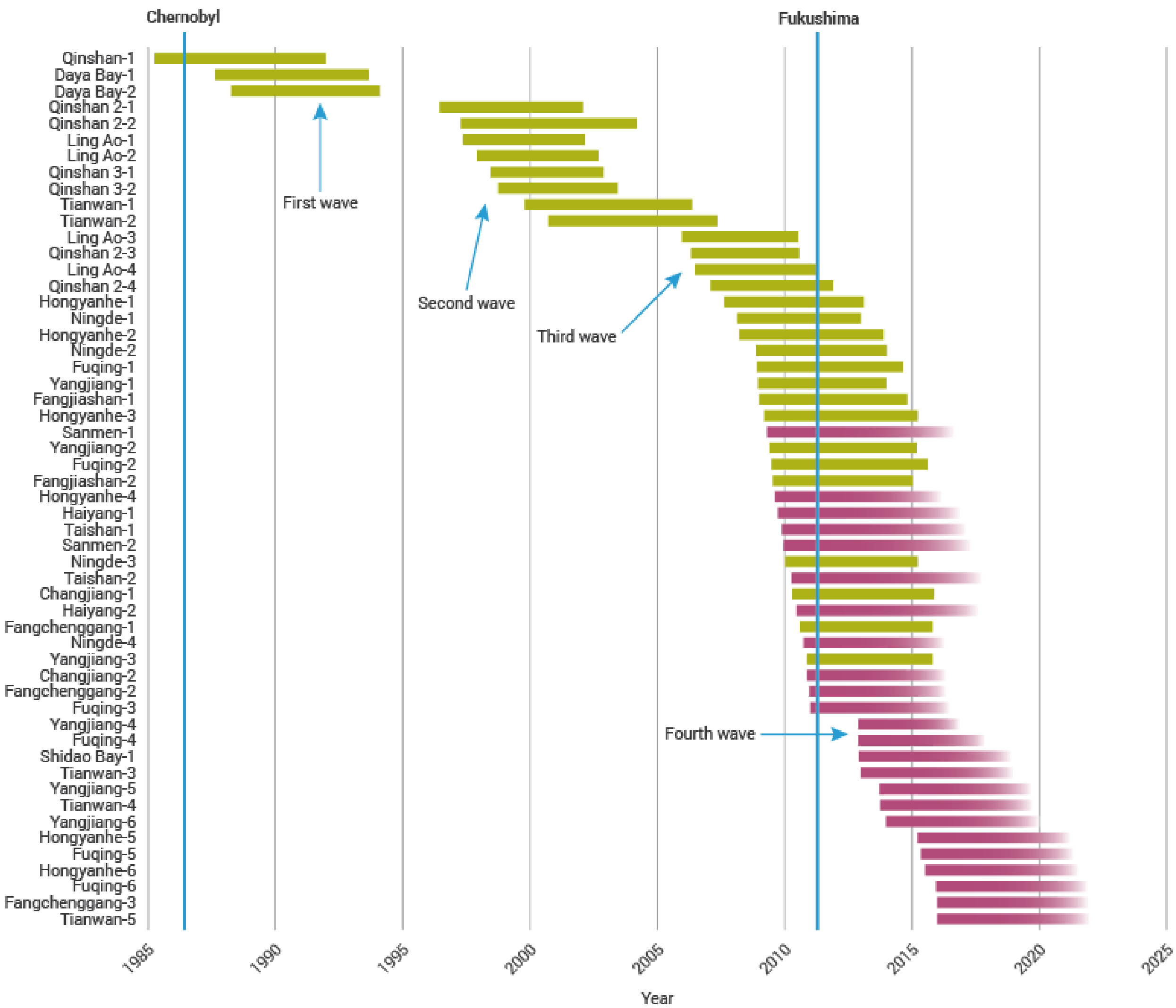

Figure 5.04: Nuclear Reactor Construction in China to Date

The third wave of Chinese reactor construction is considered to have begun in about 2006, with ground broken on the last few of the 30 third wave reactors just before the Fukushima accident in Japan in March of 2011. The Chinese nuclear establishment's response to the Fukushima accident was to order a delay in

330. Figure and related data from World Nuclear Association (2017a), "Nuclear Power in China", updated September 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.

new reactor starts while reactor safety provisions were reviewed and strengthened, and reactor deployment plans were reviewed. Subsequent to these reviews, a fourth wave of reactor construction is considered to have begun in 2012 and 2013, and has included at least 16 reactor units to date.

1.3.1 Current Fleet of Chinese Reactors

The current fleet of operating Chinese reactors, resulting from the first three waves of reactor construction described above (the fourth wave and some of the third wave plants being not yet operational) consists of 37 units totaling 33.7 GW of electricity generating capacity. Two of these units, Qinshan Phase III, units 1 and 2, are based on the CANDU heavy water/natural uranium technology (PHWRs); all the rest of the current fleet are light water reactors using low-enriched uranium fuel.[331] As shown in Figure 5.05, all existing and under-construction reactors in China are in coastal locations, and all but three nuclear plants listed as "planned" are also in coastal locations. Plants planned for inland locations, which must use river water for cooling, have been a focus of regulatory review for Chinese authorities, particularly post-Fukushima, with the reliable availability of sufficient cooling water, particularly in a changing climate regime, being a significant concern, as well as the possible pollution of rivers in the event of an accident. China's regulatory review of inland sites may have contributed to a general impression among the Chinese public that the consequences of a nuclear accident at a reactor located at an inland site will result in radioactive contamination of the river used for cooling that would be much worse than contamination of a coastal site. This impression, to the extent that it persists, may make it more difficult for reactors to be built in non-coastal areas.

331. Light water reactors, or LWRs, use regular water (H_2O) as the reactor coolant. The two primary light water reactor designs are pressurized water reactors (PWRs), which are dominant in China, and boiling water reactors (BWRs), which are also common worldwide (and of which the units at the damaged Fukushima Daiichi plant are examples). China is also building a 210 MWe high-temperature gas-cooled reactor (Model "HTR-PM") in Shandong province. The HTR-PM uses fuel spheres ("pebbles") rather than fuel encased in long metal tubes (fuel rods) like the other reactor types.

Figure 5.05: Location of Nuclear Power Plants Existing, Under Construction, and Planned in China[332]

The World Nuclear Association characterizes China's nuclear policy as:

"China has set the following points as key elements of its nuclear energy policy:

- PWRs will be the mainstream but not sole reactor type.
- Nuclear fuel assemblies are fabricated and supplied indigenously.
- Domestic manufacturing of plant and equipment will be maximised, with self-reliance in design and project management.
- International cooperation is nevertheless encouraged."

The World Nuclear Association also notes that "[t]he technology base for future reactors remains officially undefined, though two designs are currently predominant in construction plans: CAP1000 and Hualong One, after plans for more CPR-1000 units were scaled back post-Fukushima. Beyond them, high-temper-

332. World Nuclear Association (2017a), ibid.

ature gas-cooled reactors and fast reactors appear to be the main priorities." For the present, China's use of many different kinds of reactors, ordered and funded by different provinces, and only loosely coordinated with power grid development, may prove to be problematic soon, and may complicate nationally coordinated management of spent fuel.[333]

The combination of current electricity generation over-capacity, particularly in east coast areas where many reactors are located, plus the variety of reactors under construction, the poor record of many imported reactor technologies, and China's ambitions to export reactors itself, combine to yield picture of China's nuclear future that is significantly muddled relative to stated policy. The text box below, co-authored by Professor Stephen Thomas of the University of Greenwich, United Kingdom, briefly explores these issues.[334]

Box 1: China's Nuclear Export Ambitions: Prospects and Challenges[335]

China's lack of focus on one or a very few reactor designs has resulted in a technologically challenging situation as a major reactor build-out continues. China's original plan as of 2007 was to use the 1970s/1980s French reactor design for a few years, but import and indigenize state-of-the-art foreign technologies, with the goal of making reactors affordable for domestic use and for export to countries new to nuclear power, as well as to established nuclear energy users. The indigenizing of foreign technologies was to have been done through the adaptation of the Westinghouse AP1000 and to a lesser extent the French (Areva) EPR designs. Both technologies have failed badly, so China's two major reactor vendors, CGN and CNNC, have returned to the old French technology used for, for example, the units at Daya Bay, updating it and adding new features to develop the ACP-1000 and ACPR-1000 designs, which are being "merged" to yield the Hualong One. Whether this design will be safe enough to convince foreign regulators (it is being tested in the United Kingdom, which has been considering importing Chinese reactors), and still be inexpensive enough to attract buyers, remains to be seen. Another, somewhat weaker Chinese nuclear utility, SNPTC, which was set up to indigenize the AP1000 design, is scaling it up to the 1400 MWe CAP1400 design to try to make the economics more attractive, but whether doing so will be successful or not is unclear.

Despite a substantial interest in exporting reactors, and substantial effort to do so, China has been unable to reach firm agreements except for its deal with Pakistan and an agreement, but not yet a contract, to construct (or rather, to resume construction on) two CANDU units in Romania.[336] Both of these export

333. In addition, China's nuclear energy sector involves dozens of different firms and entities. Some of these are national in scope, some regional or provincial, and some organized specifically to implement a particular nuclear project. Ownership of nuclear entities is similarly complex, with national and provincial utilities being mostly state-owned, but with a variety of joint ventures and subsidiaries involving publically traded companies, private entities, and others. See World Nuclear Association (2017b), "Government Structure and Ownership: Nuclear Power in China Appendix 1", updated September 2017, available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/appendices/nuclear-power-in-china-appendix-1-government-struc.aspx.
334. For additional detail, see Steve Thomas (2017), "China's nuclear export drive: Trojan Horse or Marshall Plan?", *Energy Policy*, volume 101 (2017), pages 683–691.
335. See also Matthew Cottee (2017), "China's nuclear export ambitions run into friction", *Financial Times*, dated August 2, 2017, and available as https://www.ft.com/content/84c25750-75da-11e7-90c0-90a9d1bc9691. Interestingly this article includes the following passage about Russia's allegedly waning interest in nuclear exports: "The current leader in the nuclear export market, Russia's Rosatom, is reportedly shifting focus to hydropower and wind turbines rather than its usual reactor business. Speaking at the 'Technoprom-2017' conference in Novosibirsk, the deputy general director of Rosatom, Vyacheslav Pershukov, suggested that the export market for nuclear reactors has been exhausted."
336. See, for example, World Nuclear Association (2017c), "Nuclear Power in Romania", last updated October, 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/romania.aspx; and Stephen Stapczynski and Aibing Guo (2015), "China Widens Nuclear Exports With $7.7 Billion Romania Plant", *Bloomberg*, dated

ventures are receiving or thought to be receiving significant Chinese financing for the purchases. A number of other deals are reportedly under discussion. The lack of additional firm contracts may be because China has only entered the field of nuclear vendors during this decade, because there is reluctance to buy from China (for reasons not completely understood) or because there is simply little actual market for reactors outside of China. The contrast between Russia, which lacks the wherewithal to provide financing and significant portions of the required the supply chain to support reactor exports, but has about 30 firm orders, and China which does have the money and supply chain but has no orders, is marked.

The size of China makes analysis of its economic and technological situations hard to carry out, because its industries can dominate international markets without being dominant at home. Nuclear represents a negligible part of China's electricity mix, yet reactors built in China account for the majority of the world's nuclear construction over the last decade. As a result, one might say that that global nuclear industry needs China, but China doesn't necessarily need nuclear power. As such, the opposition by some citizen groups to building nuclear power at inland sites is very important, because it limits reactor development to the coastal areas, and in some coastal regions there is already significant generation overcapacity. Overcapacity in some parts of the coast has meant that reactors are being used for load-following—which A) they are not built for, and B) has a negative impact on their capacity factors and thus on their profitability—and new plants have even been delayed in entering service because there is insufficient electricity demand, further affecting the economics of nuclear investments.[337]

Given the challenges above, it is unclear to the authors how long the China government will put its weight behind its nuclear export industry, when the nation as a whole could win much more business and gain more political influence by putting its weight behind other technologies such as high-speed rail, in which it has had remarkable domestic success, and renewable energy, in which it has substantial and sometimes dominant market shares both at home and abroad.

1.3.2 Nuclear Fuel Cycle Facilities

China obtains portions, in some cases most, of its uranium, fuel conversion, enrichment, and fuel fabrication needs (the "front end" of the fuel cycle) from domestic resources and facilities. As a nuclear weapons state, some of these facilities were originally developed in support of China's nuclear weapons program. The World Nuclear Association describes China's policy on uranium acquisition for its nuclear power program as targeting "about one-third of uranium supply domestically, one-third from Chinese equity in foreign mines, and one-third on the open market".[338] China has seven operating uranium mines, two of which date from the 1960s and 70s, as well as uranium resources in many other locations. China has purchased a significant amount of uranium from a number of supplier nations, and two Chinese firms hold equity in uranium mines in central Asia, Africa, and Canada.

Enrichment of uranium is the process of concentrating the fraction of the U-235 isotope found in natural uranium (about 0.7 percent) to the fraction needed in LWR fuel, typically 3 to 5 percent. A preliminary step to enrichment is conversion of natural uranium oxide, a solid, to gaseous uranium hexafluoride (UF_6). The World Nuclear Association lists China's conversion capacity as somewhat uncertain, with a report of

November 9, 2017, and available as https://www.bloomberg.com/news/articles/2015-11-10/china-keeps-nuclear-exports-going-with-7-7-billion-romania-deal.

337. See C.F. Yu (2016), "CHINA: Beijing Drafts Rule to Put Reactors In Load-Following Mode", *Nuclear Intelligence Weekly*, Volume 10, No. 33, August 19, 2016, available from http://www.energyintel.com/pages/about_uiw.aspx.

338. World Nuclear Association (2017b), "China's Nuclear Fuel Cycle", updated July 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx.

a 5000 t/yr plant in Gansu province operating at 80 percent of capacity, with another 9000 t/yr plant due to come on line this year or next. A smaller plant (500 t/yr) plant is reported in northwest Gansu province. Another plant with a capacity of 3000 t/yr is reportedly being built by China Nuclear Fuel Corp in Hunan province, and will be on line in 2018.

Enrichment of uranium in China takes place at larger plants in Shanxi and Gansu provinces, and at two smaller plants in Sichuan province. The total capacity of these plants is estimated at 5.7 to 7.0 million SWU (separative work units, a measure of enrichment capacity) per year in 2015, and a projected range of 10.7 to 12.0 million SWU/yr in 2020. By way of comparison, annual enrichment demand for Chinese reactors was expected to total 9 million SWU in 2020. Enriched uranium has also been imported to China, particularly for reactors of foreign design, with enrichment services provided in Europe and Russia. Centrifuges used for enrichment were provided by Russia in the past, but indigenous centrifuges technology has been used for recent capacity expansions, starting in 2010.[339]

The fabrication of fuel for Chinese reactors is done mostly in China, with some reactors supplied by France and Russia under contract to receive fuel from those nations sufficient for the first reactor core loading and a number of subsequent loadings. A plant in Yibin, Sichuan province, with a total capacity of 900 t/yr, makes fuel for PWRs and for the Russian VVER design. A second major plant in Inner Mongolia, at Baotou, fabricates fuel for China's pair of CANDU reactors as well as for various PWR models,[340] and will reportedly have total annual capacity of 1600 t/yr by 2020. A facility at the Baotou plant is also making fuel for the high-temperature gas reactor being completed in Shandong province. Fuel pellets for the fuel assemblies for some reactor models are also sourced from Kazakhstan's Ulba Metallurgical Plant.

Most spent PWR fuel in China is currently stored in pools on reactor sites. Generally, the on-site spent fuel storage capacity at operational nuclear power plants can accommodate 10 years of spent fuel. Taking into account ongoing trends in nuclear fuel management, such as increasingly high rates of fuel burnup (which reduce the number of refueling cycles necessary), extensions of reload cycles, and the use of dense-pack storage in spent fuel pools into consideration, it is estimated that the storage capacity of present facilities can be enlarged to hold approximately 20 years' worth of spent fuel. Currently, all PWR spent fuel is in fact stored at reactor sites except for some of the spent fuel removed from the Daya Bay reactors, the first units in commercial operation in China. Since 2003, shipments of spent fuel from Daya Bay have been transported approximately twice annually to the centralized interim storage facility in Gansu province, where it is placed in wet storage facilities (away-from-reactor spent fuel pools).[341]

The facility in Gansu province, the Jiuquan Atomic Energy Complex (JAEC) as noted above, was initially developed in the 1950s and 60s to support China's nuclear weapons program. Since then, facilities for storage of civilian nuclear spent fuel have been added, as well as a pilot-scale reprocessing plant, constructed starting in 1986 but not operational until 2010, that can handle 60 tons of spent nuclear fuel (expressed as the mass of heavy metal—mostly uranium plus plutonium—abbreviated as tHM) annually.[342]

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339. Hui Zhang (2015), *China's Uranium Enrichment Capacity: Rapid Expansion to Meet Commercial Needs*, Project on Managing the Atom, Discussion Paper No. 2015-03, Belfer Center for Science and International Affairs, Harvard Kennedy School, dated August, 2015, and available as http://www.belfercenter.org/sites/default/files/legacy/files/chinasuraniumenrichmentcapacity.pdf.
340. Including the AP1000 and its Chinese variant the CAP1000, based on Westinghouse designs and intended to be the "main basis of China's move to Generation III technology" (see World Nuclear Association 2017a, ibid).
341. Liu Xuegang (2014), *Spent Nuclear Fuel Management in China*, Nautilus Institute NAPSNet Special Report, dated 5 August, 2014, and available as https://nautilus.org/napsnet/napsnet-special-reports/spent-nuclear-fuel-management-in-china/.
342. See, for example, Nuclear Threat Initiative (2011), "Jiuquan Atomic Energy Complex", last updated September 29, 2011 , and available as http://www.nti.org/learn/facilities/722/.

1.3.3 Plans and Projections for Reactor Deployment

The World Nuclear Association lists a total of 20 reactors in China as "under construction" and 30 to 40 more as "planned", mostly with an expected construction start before 2019. The under construction and planned units total 66.7 GWe.[343] In addition, the same reference lists 100 units, totaling 114.2 GWe, as "proposed", and an additional 79 units, and 90.8 GWe, proposed for the more distant future. Together, these listings plus the reactors already in operation total well over 300 GWe, over three times the size of the United States reactor fleet at its historic maximum in 2012.[344]

One recent article, citing both the World Nuclear Association source referenced above and a Chinese-language study by the Chinese Academy of Engineering lists ranges of nuclear capacities of 83.8 to 200 GWe by 2030, and 250 to 400 GWe by 2050.[345] Other reported projections provide ranges of 340 to 500 GWe by 2050,[346] 1200 TWh of generation by 2040,[347] and on the order of 250-300 GWe, by 2050, the latter in a "two-degree" scenario where fossil fuel use is largely phased out except with the use of carbon capture and storage technologies.[348] These projections for massive growth in nuclear capacity are tempered by reports identifying the significant challenges to the Chinese nuclear sector in the years to come,[349] and focusing on renewable power and efficiency as alternatives to both fossil- and nuclear generation.[350]

1.3.4 Plans for Future Nuclear Fuel Cycle Facilities

The World Nuclear Association has summarized China's known plant for future development of "front-end" (nuclear fuel supply) and "back-end" (spent fuel management) fuel cycle facilities.[351] China looks to

343. World Nuclear Association (2017a), ibid. For nuclear power plants, capacity is sometimes shown as GWe, or gigawatts of electric power, to differentiate from output expressed in terms of thermal power, which is typically about three times higher.
344. Nuclear Energy Institute (2017), "US Nuclear Generating Statistics, 1971 – 2016", updated April, 2017, and available as https://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Generating-Statistics.
345. Qiang Yue, Jingke He, Laurence Stamford, and Adisa Azapagic (2016), "Nuclear Power in China: An Analysis of the Current and Near-Future Uranium Flows", *Energy Technology*, 2017, Volume 5, Issue 5, pages 681 – 691, available as http://onlinelibrary.wiley.com/doi/10.1002/ente.201600444/epdf.
346. Brian Wang (2015), "China will complete five nuclear reactors in 2017 and double nuclear power generation to about 420 TWh by 2021", NextBigFuture, dated March 2, 2017, available as https://www.nextbigfuture.com/2017/03/china-will-complete-five-nuclear.html.
347. US Department of Energy, Energy Information Administration (2016), "China expected to account for more than half of world growth in nuclear power through 2040", dated September 28, 2016, and available as https://www.eia.gov/todayinenergy/detail.php?id=28132, 1200 TWh at an average annual capacity factor of 80 percent would translate into about 170 GWe of nuclear generation capacity.
348. International Energy Agency/Nuclear Energy Agency (2015), *Technology Roadmaps: Nuclear Energy, 2015 Edition*, available as https://www.iea.org/media/freepublications/technologyroadmaps/TechnologyRoadmapNuclearEnergy.pdf.
349 See, for example, Xu Yi-chong (2016), "China's contested nuclear future: The expansion of China's nuclear power production faces some serious challenges", Asia Pacific Policy Forum, dated 5 February 2016, and available as https://www.policyforum.net/chinas-contested-nuclear-future/. This article cites challenges to nuclear build-out including difficulties in reactor siting, the use of multiple technologies as an impediment to cost reduction and regulation, other challenges in organizing and making effective the regulation of the industry, and competitive realities associated with the slowdown in the growth of electricity demand coupled with the growth of deployment of and ongoing cost reduction in the renewable power industries.
350. Energy Research Institute, Lawrence Berkeley National Laboratory, and Rocky Mountain Institute (2016), *Reinventing Fire: China, Executive Summary* dated September 2016, and available as https://www.rmi.org/wp-content/uploads/2017/05/OCS_Report_ReinventingFireChina_2016.pdf. Graphics in this document suggest that under a "Reinventing Fire" scenario, China's electricity generation from nuclear power in 2050 would be about 1300-1400 TWh, or the equivalent of about 190 GWe of capacity at an average capacity factor of 80 percent.
351. World Nuclear Association (2017b), ibid.

expand a number of mining activities, including, interestingly, extraction of uranium from coal ash from a power station in Yunnan province. Even with such expansions, based on at least one analysis,[352] it seems unlikely that China will be able to produce one-third of its uranium needs domestically, thus the significant emphasis by Chinese firms on investments in and joint ventures with companies prospecting for and producing uranium abroad.

Hui Zhang of Harvard University's Project on Managing the Atom, in a 2015 report, suggests, based on interviews with Chinese experts, that Chinese capacity to expand its enrichment capacity in the late 2010s was about 1 million SWU per year.[353] Given existing capacity, ongoing expansion, and the importation of initial cores for several reactors built with imported technology, Zhang estimates that China will easily have sufficient enrichment capacity to meet domestic needs through 2020, and perhaps will be able to sell surplus enrichment services internationally, "consistent with the government's stated policy of 'self-sufficiency' and 'targeting the international markets' in the supply of enrichment services". Information on China's plans for expansion of enrichment capacity beyond 2020 was not immediately available, but it seems likely that continued expansion of domestic facilities, coupled with the availability of capacity internationally, will be sufficient to fuel China's reactors on an ongoing basis.

Data provided by the World Nuclear Association suggests that China will have fuel fabrication facilities for PWRs of about 2400 tU/yr by 2020, sufficient to meet demand by that year. Some fabricated fuel is imported, particularly, as noted above, for the new cores of reactors built with imported technology. Information on plans for expansion of fuel fabrication facilities, as with enrichment, was not immediately available, but it is assumed that the China National Nuclear Corporation (CNNC), as the entity responsible for fuel fabrication in China, will continue to expand capacity to meet domestic demand, and possibly some fuel exports as well.

Reports indicate at least two ongoing efforts by China to build new facilities for reprocessing spent PWR fuel to separate plutonium for use in mixed-oxide fuel and, eventually, for use in fast reactors. A "medium scale" facility with a capacity of 200 tHM/yr is to be built at a site in Gansu province about 100 km away from the existing pilot-scale reprocessing plant described above. The medium-scale plant is part of an overall project of CNNC called "Long Teng 2020" (Dragon Soars 2020). The overall project was reported to have an expected cost 100 billion RMB (about USD 16 billion),[354] of which the reprocessing plant is an unspecified fraction, although an independent estimate provides a range of USD 3.2 to 5.7 billion (capital costs only).[355] In addition, CNNC is also negotiating with the multinational nuclear fuel cycle vendor Areva to develop an 800 tHM/yr reprocessing facility at a site on China's east coast. At 800 tHM/yr, this facility would be the size of Japan's Rokkasho reprocessing facility.

Overall, as reported by the World Nuclear Association, China is researching (in a program dating back to 1964) and plans use of "recycled" fuel on three tracks, as summarized in Figure 5.06. First, mixed-oxide fuel (MOX), which blends uranium with plutonium recovered from spent fuel during reprocessing, will be used in existing and new PWRs. Second, MOX will ultimately be used for fuel a new set of Fast Neutron, or Fast Breeder Reactors (FBRs in the Figure below). A small test fast reactor, the Chinese Experimental

352. Qiang Yue, Jingke He, Laurence Stamford, and Adisa Azapagic (2016), ibid.
353. Zhang (2015), ibid.
354. Hui Zhang (2015), "China is said to be building a demonstration commercial reprocessing plant", International Panel on Fissile Materials, dated September 23, 2015, and available as http://fissilematerials.org/blog/2015/09/china_is_said_to_be_build.html.
355. Matthew Bunn, Hui Zhang, and Li Kang (2016), *The Cost of Reprocessing in China*, Project on Managing the Atom Report, Belfer Center for Science and International Affairs, Harvard Kennedy School, dated January, 2016, and available as http://www.belfercenter.org/sites/default/files/legacy/files/The%20Cost%20of%20Reprocessing.pdf.

Fast Reactor, was built near Beijing was with Russian collaboration, and started operation in 2011. A larger test fast reactor (600 MWe) is scheduled to be constructed stating in December 2017, with operation in 2023. Assuming a positive decision for deployment in 2020, China's first commercial fast reactor (the Chinese Commercial Fast Reactor, listed at 1000 to 1200 MWe) will be constructed starting in 2028, with commissioning in 2034. Fast reactor capacity of 40 GWe is "envisaged" by 2050. Third, a blend of plutonium and recycled uranium from reprocessing of PWR fuel, plus and depleted uranium from enrichment, will be used in pressurized heavy water reactors (CANDU units, or PHWRs). A test of the use of blended recycled fuels in unit 1 of the Qinshan Phase III PHWRs was carried out, and deployment of the recycled fuels in both PHWR units was planned for 2018.

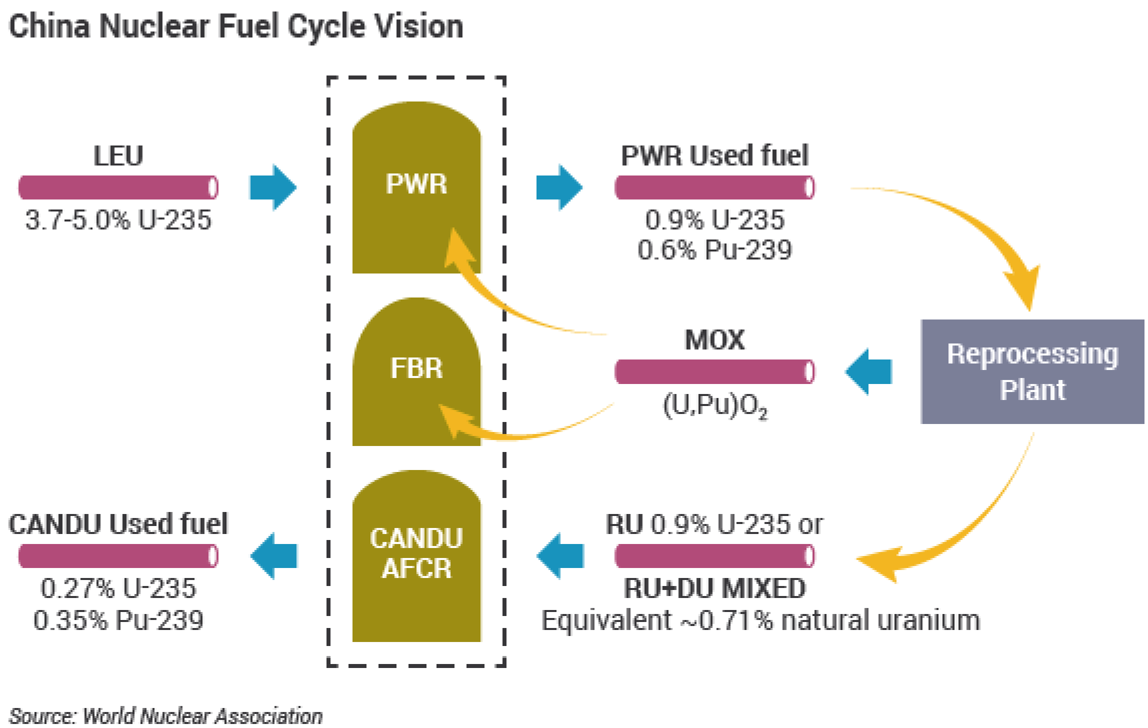

Figure 5.06: Nuclear Fuel Cycles Planned for China[356]

Apart from reprocessing, with regard to spent fuel management in China, a report on spent fuel storage by Professor Liu Xuegang concluded, in part:[357]

"Dry storage is currently only used for CANDU reactors in China, and will be implemented for HTR spent fuel. These two reactor models account for only a minor portion of the whole Chinese nuclear fleet. But the utilization of dry storage and its performance will have a great impact on future decision-making for the sector. Though some experts consider that the pool capacity at reactors in China is large enough to accommodate spent fuel for the next 5 to 10 years, there are strong voices supporting the building of a large-scale centralized spent fuel storage facility soon. In part, it is argued, the current practice of pool storage for spent fuel in highly dense packed arrays has been subject to criticism following the Fukushima accident. In case dense-racking is ultimately not chosen as a means of spent fuel storage in China, the decrease in potential spent fuel storage density will result in a lack of storage space at Chinese reactors

356. World Nuclear Association (2017b), ibid.
357. Liu Xuegang (2014), ibid.

relatively soon. For at-reactor storage, it is difficult to build new pools to store spent fuel due to the complexity of the pool systems. Dry storage is very promising in those cases. For centralized storage away from reactors, dry storage is still a strong competitor to pool-type storage due to advantages such as low investment, modular design, and easy maintenance. As a result, though dry storage has not been adopted for PWR spent fuel storage in China, the utilization of dry storage facilities is a strong possibility in the short or medium-term."

In essence, it is clear that China is still keeping multiple options open, from once-through fuel cycles with medium-term spent fuel storage in dry casks to fast reactor options with reprocessing of spent PWR fuel, and authorities have not yet converged on a single path for the nuclear sector. But as spent fuel builds up at existing reactors, reaching decisions regarding the future management of nuclear spent fuel will become more imperative.

2 Summary of Business-As-Usual/Baseline/Reference Electricity Sector Scenario for China

2.1 Introduction

The current status of and recent trends in China's electricity sector, as described above, forms the basis from which the sector, and the nuclear energy components thereof, will evolve in the future. Although many types of "disruptive" events can occur to suddenly change how the electricity system may evolve—an accident at (as in Fukushima) or attack on a nuclear facility being a prime, but hardly exclusive, example—in general projections of electricity futures assume continuations of existing trends, informed by expected changes in demographics, economic development, regional, national, and international policies, and other "drivers". To systematically compare policy-driven scenarios for electricity sector development, it is important to start with a "reference" case for development of the sector (and the economy in which it is embedded) to provide a consistent basis for comparison of both qualitative and quantitative attributes between scenarios. Such a reference, or "business as usual" (BAU) case is described briefly below, prepared as a composite of several studies of China's electricity future. This BAU case serves as the basis for exploration of the alternative scenarios presented in Section 3 of this paper.

2.2 Description of Composite BAU Scenario

The BAU (or reference) scenario presented here represents a composite of a number of literature sources, including work by the US DOE EIA, British Petroleum, Lawrence Berkeley National Laboratory, and others as described in Section 3. The focus is on the future of electricity generation in China, and in particular, nuclear energy's role in same, but more general economy-wide metrics are provided as points of reference and comparison with other studies.

Some of the key general parameters of the BAU Scenario for China are as follows:

- Reflecting the maturing Chinese economy, gross domestic product (GDP) growth slows over time, averaging 5.8 percent annually from 2015 through 2020 and 5.4%/yr from 2020 through 2030, but slowing to 3.5%/yr from 2030 through 2050, and 2.5%/yr from 2040 through 2050.[358]

358. Projections shown here are consistent with those included in the US DOE Energy Information Administration (USDOE EIA, 2017) *International Energy Outlook, 2017*, as included in the downloaded table "World gross domestic product (GDP)

- As projected by the United Nations, China's population growth slows through 2030, when it peaks at about 1.45 billion, declining thereafter to about 1.37 billion by 2050.[359]

- Growth in electricity generation also slows, continuing recent trends. Generation (and thus consumption, which is equal to generation less transmission and distribution losses) growth falls from 6.8 percent annually in the first half of the 2010s to 3.5%/yr from 2015 through 2020, then to 1.75%/yr from 2020 through 2030, 1.3%/yr from 2030 through 2040, and 0.8 percent annually thereafter through 2050.[360] This trend is another reflection of a maturing economy and, coupled with continuing (though declining) GDP growth, results in falling energy intensity per unit of GDP. The declining population after 2030, however, means that growth in electricity production (and use) per person grows faster than overall electricity use, increasing, for example, at 1.5%/yr from 2030 through 2040, and 1.2%/yr from 2040 through 2050.

- While total electricity generation nearly doubles, from about 5700 TWh in 2015 to over 10,000 TWh by 2050, shares of electricity generation in China continue to shift over time, as shown in Figure 5.07. The share of electricity output provided by coal-fired power declines from about 70 percent in 2015 to slightly over 40 percent by 2050, with growth in gas-fired, wind, and nuclear generation providing nearly all of the displacement. Hydroelectric generation, as a share of the total, changes relatively little over time, solar grows substantially but to only 4.1 percent of generation by 2050, and the use of liquid petroleum products, never a large fraction of generation in China, continues to decline. Nuclear power's share of generation grows to 13 percent by 2050, but most of the growth in its share of the power market occurs before 2030.

- Changes in generation capacity by type, as shown in Figure 5.08, reflect the same general trends as in electricity generation itself, except that wind and solar power, due to their lower capacity factors (operating fewer hours per year due the intermittent availability of wind and solar resources) relative to coal-fired and nuclear units, account for a larger share of added and total generation capacity. Natural-gas-fired power undergoes a shift from being mostly a peak resource, with low capacity factors (23 percent in 2015 and 2020) to being mostly a baseload resource (capacity factor of over 60 percent in 2050), reflecting a shift from simple-cycle gas turbines to more efficient combined-cycle plants.

- Total Nuclear generation capacity in the BAU case rises to about 140 GW in 2040, and 170 GW in 2050. As such, it assumes a slightly reduced growth trend, particularly after 2040, than the BAU projections for capacity provided in the USDOE's most recent *International Energy Outlook*, which calls for 139 GW of generation in 2040, and 187 GW in 2050.

Additional details on the nuclear fuel cycle elements of the BAU scenario are provided in section 3, below.

by region expressed in market exchange rates", available from https://www.eia.gov/outlooks/aeo/data/browser/#/?id=4-IEO2016&cases=Reference&sourcekey=0. Note that GDP growth values are not used as direct drivers of electricity consumption in the BAU scenario presented here, but are provided for reference.

359. United Nations Department of Economic and Social Affairs, Population Division (2017), *World Population Prospects: The 2017 Revision*, dated June, 2017. Data shown are based on data for China in table "Medium fertility variant, 2015 – 2100". Downloaded File WPP2017_POP_F01_1_TOTAL_POPULATION_BOTH_SEXES.xlsx.

360. These increases in electricity use are generally consistent with the BAU scenario for China included the USDOE EIA *International Energy Outlook, 2017* document, as referenced above.

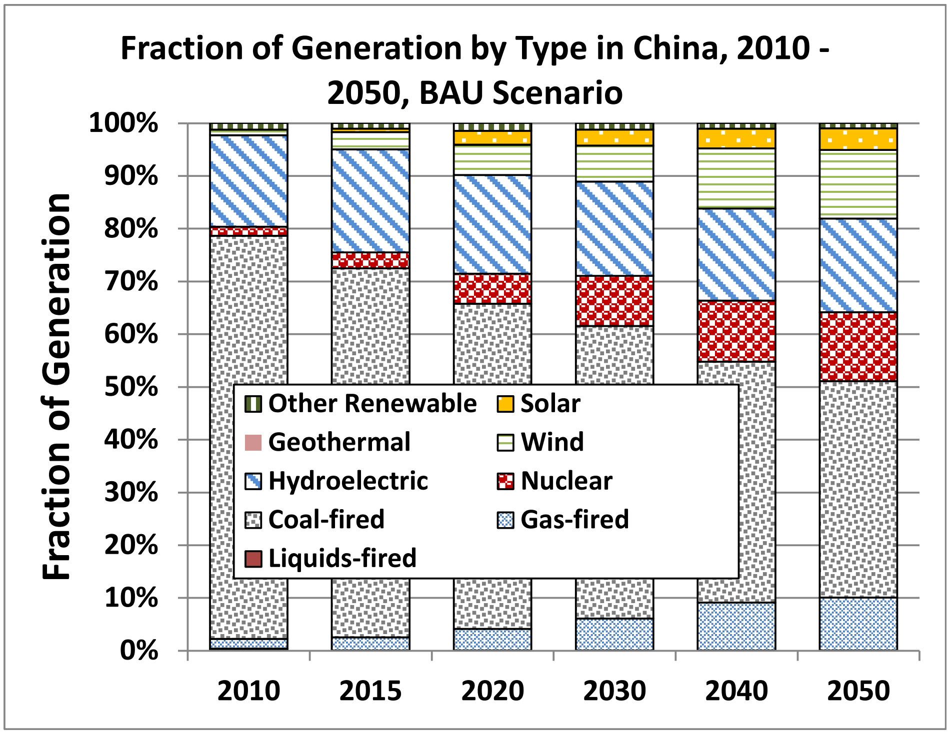

Figure 5.07

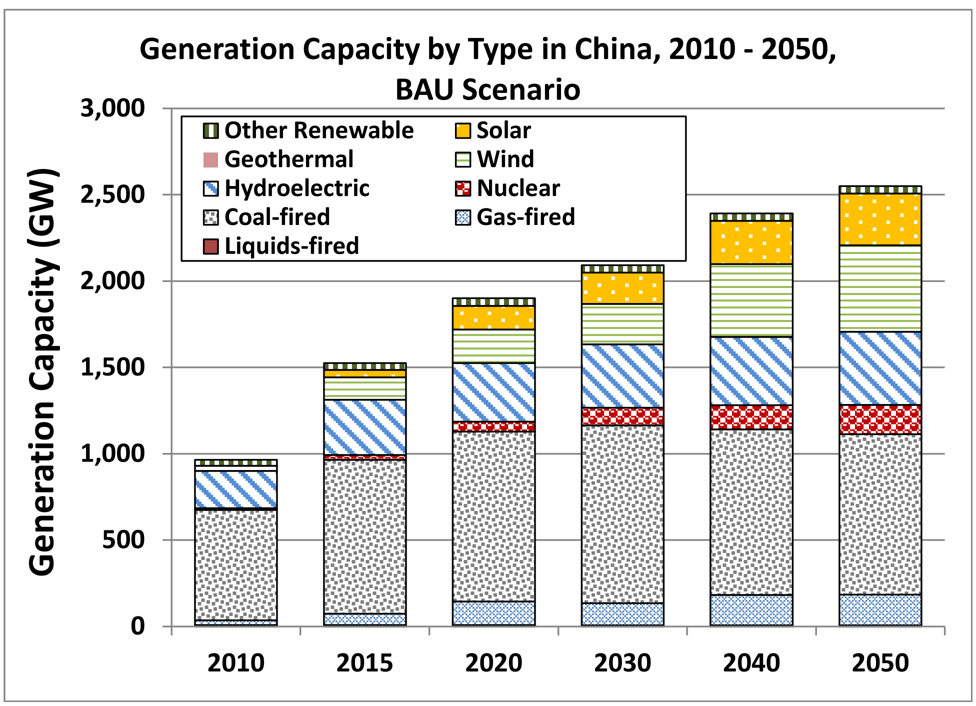

Figure 5.08

3 *Alternative Scenarios for China's Energy and Nuclear Future*

3.1 Introduction—Focus of Alternative Scenarios and Key Examples

Alternative scenarios, or alternative projections (which are not necessarily the same thing), can be prepared to demonstrate different potential energy futures for a nation, state, province, city, region, or other jurisdiction. Scenarios and projections are thus tools that analysts, and the policymakers they serve or seek to influence, use to test how policies devised and implemented in the near or more distant future are likely to affect key metrics that are of concern to policymakers and to society as a whole. These metrics will typically include quantitative measures such as total energy or electricity use, total cost, and emissions of local and greenhouse gas pollutants, but may also include qualitative metrics such as the expected impact on energy or military security, environmental or political risk, or social impacts.

As there are literally an infinite number of future scenarios and projections that can be chosen, it is important for analysts to select examples for comparison that are plausible—though looking out more than 30 years into the future is by definition an exercise in speculation—yet are sufficiently different that the comparison of the different cases yield policy-relevant insights. At the same time, the different scenarios/projections should typically be configured to provide the same *energy services*, that is, for example, to support economies of roughly the same size and growth rate, to move the same number of people the same distance (if not always by the same modes), and to heat homes and cool to the same degree, though not always with the same energy sources. For the different China energy futures we describe below—focusing on electricity—we have defined scenarios/projections that support approximately the same economic structure and GDP growth rates, and the same populations, but are quite different in terms of how the energy systems, and especially the electricity and nuclear energy sectors, might evolve.

Given the global importance of the Chinese energy sector, a number of different groups have, over the past several years, prepared their own versions of how energy supply and demand in China might evolve through 2040 or 2050. Some notable examples include:

- The US Department of Energy's Energy Information Administration projections as a part of their *International Energy Outlook* series, the 2016 and 2017 versions of which have been used to help define the BAU case projections for the Chinese electricity sector presented in section 2 of this paper.
- Work by the China Energy Group of Lawrence Berkeley National Laboratory (LBNL), including studies developing and analyzing scenarios for the evolution of China's energy sector through 2050.
- Work by the Rocky Mountain Institute and LBNL under the "Reinventing Fire" project, which looks at scenarios to vastly reduce energy sector greenhouse gas emissions in several countries, including China.
- A study of scenarios of the Chinese power sector by a group from the Renewable and Appropriate Energy Laboratory of the University of California-Berkeley.
- Work by Greenpeace, including on the future of nuclear and coal-fired power in China, and scenarios of accelerated deployment of renewable energy systems.
- Scenarios of the evolution of the energy sector published by the Energy Research Institute (ERI) of the National Development and Reform Commission (NDRC).

- Continuing work under the China Renewable Energy Outlook project, implemented by ERI and the China National Renewable Energy Centre (CNREC), with cooperation from the Danish Energy Agency and the US National Renewable Energy Laboratory (NREL).

Brief summaries of each of these efforts are presented briefly below, followed by quantitative and qualitative comparisons of three "composite" scenarios that draw from these studies and others, and feature deployment of nuclear energy at different levels.

3.2 Summary of Examples of Alternative Scenarios

Alternative scenarios explore and project futures for China's energy sector that are different than a reference or business-as-usual case, and thus reflect the application of policies designed to steer the energy sector in a given direction, the influence of changes in the energy sector (or broader economy and society) not anticipated in the reference case, or both. Summaries of several alternative energy and, especially, electricity-sector scenarios for China are provided below. Most of these scenarios focus primarily on accelerated implementation of energy efficiency and/or renewable energy, relative to a reference case, but each could or would have significant implications for the nuclear energy sector as well.

3.2.1 Lawrence Berkeley National Laboratory (LBNL) China Energy Group

The researchers in the China Energy Group of the Energy Analysis and Environmental Impacts Division of LBNL have carried out a number of studies in which they have developed scenarios of China's energy future, usually focusing on energy efficiency and/or reducing greenhouse gas emissions.[361] A recent (2017) publication by the China Energy Group compares a "reference case" with alternative cases for electricity demand. A "Cost-effective Efficiency and Renewables Scenario" reduced year-2050 electricity demand by 21 percent, relative to the reference case, and a "Maximum Electrification Scenario"—based on the Cost-effective Efficiency and Renewables Scenario, but incorporating additional electrification in all sectors— still reduced 2050 electricity demand by 13 percent. Both of these scenarios resulted in a reduction of over 50 percent in national CO_2 emissions in year 2050 relative to the reference case (from 11.57 billion tons, or Gt, CO_2 to 4.79 and 4.72 Gt CO_2, respectively). A third alternative scenario, including maximum deployment of demand-side renewables, offered additional reductions, to 3.98 Gt CO_2 by 2050. By way of comparison, China's 2016 CO_2 emissions stood at about 10 Gt, so each of the alternative scenarios represents a significant reduction, by 2050, relative to current emissions.[362]

361. See, for example, Nina Khanna, David Fridley, Nan Zhou, Nihan Karali, Jingjing Zhang, and Wei Feng (2017), "China's Trajectories beyond Efficiency: CO_2 Implications of Maximizing Electrification and Renewable Resources through 2050", dated May, 2017, prepared for the European Council for an Energy Efficient Economy's 2017 Summer Study, and available as https://china.lbl.gov/sites/default/files/1-142-17_zheng_khanna_final.pdf. The China Energy Group uses the LEAP (Long-range Energy Alternatives Planning) software tool developed by the Stockholm Environment Institute—United States to quantitatively model energy flows, emissions, and other parameters for China in LBNL's China 2050 Demand Resources Energy Analysis Model (DREAM).

362. See, for example, Zhu Liu (2016), *China's Carbon Emissions Report 2016: Regional Carbon Emissions and the Implication for China's Low Carbon Development*, Environment & Natural Resources Program, Belfer Center for Science and International Affairs, Harvard Kennedy School, dated October, 2016, and available as https://www.belfercenter.org/sites/default/files/files/publication/China%20Carbon%20Emissions%202016%20final%20web.pdf; and David Fridley, Hongyou Lu, and Xu Liu (2017), *Key China Energy Statistics 2016*, available as https://china.lbl.gov/sites/default/files/ced-9-2017-final.

In a 2016 study focused on energy demand and CO2 emissions in China's cities—which produce on the order of 75-80 percent of China's national CO2 emissions in recent years—LBNL China Energy Group researchers evaluated a "Low Carbon" scenario representing "a pathway in which commercially-available cost-effective efficiency and renewable energy technologies are fully deployed". [363] The measures included in the Low Carbon scenario reduced year 2050 reference case urban emissions by approximately two-thirds, a result consistent with the findings in the 2017 study detailed above.

In a 2016 study focusing on the implications of power-sector policies on coal-fired generation and CO_2 emissions in China, the China Energy Group projected that a "Strengthened renewable MMS [mandatory market share] with green dispatch scenario" could reduce coal-fired generation to 14 percent of total generation by 2050.[364] In the same scenario, renewable power generation (biomass, wind, solar, and hydro) provides about 63 percent of generation in 2050, with output of "renewables" (inferred in this case to mean wind, solar, and biomass) reported at 4472 TWh, and nuclear power providing about 20 percent of total generation. At that level of nuclear generation, the implied capacity of nuclear power assumed in the Strengthened renewable MMS with green dispatch scenario would be nearly 300 GW.[365]

3.2.2 *Rocky Mountain Institute, LBNL, and Energy Research Institute "Reinventing Fire" Project*

An ongoing collaboration between the Rocky Mountain Institute (RMI), LBNL, and the Energy Research Institute (ERI) of the of the National Development and Reform Commission of China (see below), the "Reinventing Fire" project seeks to identify pathways of deep carbon dioxide emissions reduction through a combination of energy efficiency, electrification of end-uses that currently use fossil fuels, and expanded deployment of renewable electricity. The collaboration draws on work by all three partners, including the LBNL and ERI described above and below, respectively. An Executive Summary of the *Reinventing Fire* report from 2016 shows a reference case in which electricity generation rises to 12,800 TWh by 2050, up from 4,700 TWh in a 2011 base year.[366] In the "Reinventing Fire" case, electricity generation in 2050 falls by 16 percent relative to the reference scenario, to 10,800 TWh, as a result of two partially offsetting sets of policies. Energy efficiency reduces 2050 electricity demand by on the order of 6,000 TWh, relative to the reference case, while electrification displacing fossil fuel use throughout the economy adds back 4,000 TWh to the 2050 total. Additional renewable electricity generation in the Reinventing Fire scenario displaces about 3,000 TWh of fossil and some nuclear generation in 2050, relative to the reference case. Nuclear generation in 2050 in the Reinventing Fire case is about 1,550 TWh, as opposed to about 2,400 TWh in the reference case. These values correspond to 2050 nuclear capacities of about 210 and 320 GW,

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pdf.

363. Nina Z. Khanna, David Fridley, Lynn Price, Nan Zhou, and Stephanie Ohshita (2016), "Estimating China's Urban Energy Demand and CO2 Emissions: A Bottom-up Modeling Perspective", 2016 ACEEE Summer Study on Energy Efficiency in Buildings, available as https://china.lbl.gov/sites/default/files/11_129.pdf,

364. Nina Zheng Khanna, Nan Zhou, David Fridley, and Jing Ke (2016), "Quantifying the potential impacts of China's power-sector policies on coal input and CO_2 emissions through 2050: A bottom-up perspective", *Utilities Policy*, Volume 41, August 2016, Pages 128-138, available as available from https://eta.lbl.gov/publications/quantifying-potential-impacts-chinas.

365. Estimate of implied nuclear capacity by the author of this paper is based on review of Figure 3 in Khanna et al, 2016 (ibid), and assuming an average capacity factor for nuclear generation in 2050 of 85 percent. Reference case generation in 2050 was reported as 10,730 TWh.

366. ERI, LBNL, and RMI (2016), *Reinventing Fire: China, A Roadmap For China's Revolution in Energy Consumption and Production To 2050, Executive Summary*, dated September, 2016, and available from https://www.rmi.org/insights/reports/reinventing-fire-china/.

respectively, assuming an average capacity factor for nuclear generation of 85 percent in 2050.[367]

Real GDP growth in both cases was assumed to be slightly higher than that included in the BAU case outlined in Section 2.2, above, at annual averages of 7.18 percent from 2010-2020, 5.60 percent from 2020-2030, 4.12 percent from 2030-2040, and 2.94 percent from 2040-2050. Population growth assumptions were similar to those in the United Nations "Medium Variant" projections reported above.

The net result of the Reinventing Fire scenario is to essentially cut in half year 2050 primary energy requirements relative to the reference case, bringing overall primary energy use by the Chinese economy back to 2050 levels. Overall 2050 CO_2 emissions similarly fall by nearly half in the Reinventing Fire case, relative to the Reference case. Emissions of the local and regional air pollutants sulfur and nitrogen oxides fall by factors of approximately 8 and 12, respectively, relative to 2010 level, in the Reinventing Fire scenario. Further, the authors of the report find a net direct economic benefit due to the transition to the Reinventing Fire scenario. The Reinventing Fire Scenario will

> "…save China 21 trillion RMB in energy costs. From 2010 to 2050, implementing the Reinventing Fire Scenario yields a potential energy savings of 56 trillion RMB ($8.3 trillion) relative to the Reference Scenario. Incremental new investment required beyond the Reference Scenario to realize these energy savings is estimated to be 35 trillion RMB ($5.2 trillion), yielding a net present value savings of 21 trillion RMB ($3.1 trillion, all figures 2010 real)."

3.2.3 *"SWITCH-China" Modeling by UC Berkeley Renewable and Appropriate Energy Laboratory*

SWITCH-China is an integrated model of the Chinese electricity sector prepared by researchers at the University of California's Renewable and Appropriate Energy Laboratory (RAEL) and their colleagues.[368] In a 2016 study, the SWITCH-China model was used to investigate four scenarios of the evolution of carbon emissions by the Chinese power sector. The most stringent of these, the "IPCC Scenario", includes on the order of 250-300 GWe of nuclear generation capacity by 2050,[369] meeting 14 percent of total electricity demand, along with about 1500 GWe of wind power, about 1900 GWe of solar power, and 500 GWe of electricity storage. By 2050, about 90 percent of coal-fired generation (providing in total 29 percent of China's 2050 electricity needs) is coupled with carbon capture and sequestration (CCS) systems. CCS systems collect carbon dioxide from power plant exhaust gases (using considerable energy in the process) for sequestration in (typically) underground strata.

The SWITCH-China IPCC case results in a reduction of power-sector CO_2 emissions to 80 percent of 1990 levels. The authors of the study report that the annual additional cost of the scenario is over $2 trillion per year by 2050, which is offset at least partially ("22 to 42 percent) by the avoided external costs of coal production and use in the IPCC scenario. Placed in context, $2 trillion is about 5-7 percent of projected Chinese GDP in 2050. It should be noted that the SWITCH-China Reference Case appears to call for considerably higher growth in overall generation capacity, and thus likely in generation, relative to the composite BAU scenario described in section 2.2 of this paper.

367. Nuclear generation values estimated by the author of this paper from data presented in Figure ES-14 in ERI, LBNL, and RMI (2016), ibid.
368. Gang He, Anne-Perrine Avrin, James H. Nelson, Josiah Johnston, Ana Mileva, Jianwei Tian, and Daniel M. Kammen (2016), "SWITCH-China: A Systems Approach to Decarbonizing China's Power System", *Environmental Science and Technology,* 2016, 50 (11), pp 5467–5473, available as http://pubs.acs.org/doi/abs/10.1021/acs.est.6b01345.
369. Capacity estimates are by the author of this paper based on review of figures in He et al (2016).

3.2.4 Commentary on Plans for Nuclear and Coal-fired Power Development by Greenpeace

Although the author of this paper was unable to find long-range projections of the evolution of the Chinese energy sector authored by Greenpeace that are similar to the studies described above, a number of Greenpeace publications have commented on the future of the Chinese coal and nuclear sectors. A 2012 article suggests that China should focus on renewable energy and energy efficiency to reduce greenhouse gas emissions, and that

> "…building enough nuclear power stations to make a meaningful reduction in greenhouse gas emissions would cost trillions of dollars, create tens of thousands of tons of lethal high-level radioactive waste, contribute to further proliferation of nuclear weapons materials, and result in a Chernobyl-scale accident once every decade. Perhaps most significantly, it will squander the resources necessary to implement meaningful climate change solutions."[370]

A late 2017 article notes that China has recently canceled or delayed work on more than 150 planned or under-construction coal-fired power plants due to the "flat-lining" of demand for coal-fired power due to overcapacity of coal-fired generation. The article cites the environmental benefits of not moving forward with coal-fired power, including air pollution and water consumption benefits, and indicates that newly-increased targets for deployment of solar and wind power sources will further reduce the need for coal-fired generation. The article also notes that "[t]he government's recent efforts to clamp down on the red-hot real estate sector and local government debt spending – key drivers of China's heavy industry volumes and power demand – will also leave less space for coal-fired power generation."[371]

A Greenpeace report evaluated the co-benefits of renewable generation in China from 2015 through 2030.[372] Among other findings, the report:

- Finds that the external environmental benefits of renewable generation exceed the wind power subsidy provided even in 2016,[373] and will be more than twice the level of the subsidy by 2030.
- States that "Between 2015 and 2030, wind and solar PV power will contribute RMB 14.3 trillion to China's GDP".
- Estimates that the wind and solar industries will employ 7.7 million people by 2030.
- Indicates that solar energy has been a force in "energy poverty" alleviation by being a major tool for providing electricity to households that previously lacked grid access.
- Notes that wind and solar development has reduced water use by coal-fired power plants, with the reduction by 2030 "… expected to increase to 3.6 billion m^3, equivalent to the annual basic water consumption of 200 million people".

A 2016 article provided by Greenpeace identifies some of the issues affecting deployment of reactors in

370. Greenpeace East Asia (2012), "No nuclear in China - not anywhere", dated 10-31-2012, and available as http://www.greenpeace.org/eastasia/news/blog/no-nuclear-in-china-not-anywhere/blog/42752/.
371. Lauri Myllyvirta and Li Danqing (2017), China halts more than 150 coal-fired power plants", dated October 11, 2017, and available as https://unearthed.greenpeace.org/2017/10/11/china-halts-150-coal-fired-power-plants/.
372. Greenpeace (2017), *Accelerating the Energy Transition The Co-benefits of Wind and Solar PV Power in China, Summary* dated April, 2017, and available as https://secured-static.greenpeace.org/eastasia/PageFiles/299371/Renewables%20co-benefits%20report,%20April%2017/Accelerating%20the%20Energy%20Transition_GPEA%20media%20briefing_0411.pdf.
373. The subsidy location cited is n Zhangjiakou, Hebei Province, where the wind power generation subsidy was 0.14 RMB/kWh in 2016.

China based on imported designs, and suggests that these issues will make China's ambitious nuclear power development targets difficult to achieve.[374]

3.2.5 China National Renewable Energy Center's "China Renewable Energy Outlook 2016" (CREO)

The report *China Renewable Energy Outlook 2016*, prepared by the China Renewable Energy Center in collaboration with groups in China, Europe, and the United States, focuses on an alternative "High Renewable Energy (RE) Penetration" scenario to a "Stated Policies" reference case, both evaluated through 2030.[375] The two scenarios differ only modestly with regard to overall energy consumption, with the stated policies case reaching a slightly higher peak in overall energy consumption a few years later than the high RE penetration case, and having a somewhat slower decline in contribution of coal to primary energy use (47 percent of total primary energy in 2030 in the Stated Policy scenario versus 42 percent in the High RE Penetration scenario, down from 65 percent in 2016). The High RE Penetration case, however, provides a third more RE energy production by 2030 than the Stated Policies case. This difference is accomplished mainly by adding over 1000 GW of mainly wind and solar generation capacity in the High RE Penetration scenario, over and above the amounts assumed for the Stated Policies case. Coal-fired capacity falls from a high of 960 GW in 2020 in both scenarios, to 710 GW in the Stated Policies case and 660 GW in the High RE Penetration scenario, Generation from coal-fired power plants falls more dramatically, however, and as a result CO_2 emissions are 1.25 billion tons lower (about 13 percent) in the High RE Penetration scenario, and local air pollution and its health effects fall much more rapidly as well. The CREO report estimated a small increase in GDP in the High RE Penetration case relative to the Stated Policies case, with a significant boost to employment in renewable energy-related occupations partially offset by a reduction in employment in the fossil fuels sectors, mostly coal mining.

With regard to the nuclear sector, the CREO report includes the following description:

> "According to the decisions by the previous as well as current government of China, construction of nuclear power plants in the inland and in large-scale construction in the Yangtze River Basin will not happen. The development of the western regions has priority for a "green mountains and clear water are as good as mountains of gold and silver", primarily based on renewable energy. Before the fourth generation of nuclear power technology is in commercial operation, it is assumed that China will not open the inland deployment of nuclear power. Based on this, we consider nuclear power development to be within the range of 100 GW in 2050, solely deployed in coastal areas."

Although nuclear deployment in the two scenarios considered in the CREO 2016 report does not different markedly, with nuclear development limited to 75 GW by 2030, CREO thus projects much less nuclear capacity than that implied by the roster of planned reactors presented by the World Nuclear Association (as described above), but still creates significant environmental benefits, relative to the Stated Policies case, through the High RE Penetration scenario.

The CREO project partners have been updating and expanded their analyses, and a "CREO 2017" report is forthcoming.

374. Zachary Davies Boren (2016), "All is not well with nuclear in China", dated February 17, 2016, and available as http://energydesk.greenpeace.org/2016/02/17/not-even-china-likes-the-hinkley-epr-nuclear-reactor/.

375. China National Renewable Energy Center and Energy Research Institute (CNREC and ERI, 2016), *China Renewable Energy Outlook 2016*, prepared with cooperation partners the Danish Energy Agency and the US National Renewable Energy Laboratory, and available as http://www.ea-energianalyse.dk/reports/1473_REO2016.pdf.

3.2.6 *Energy Research Institute's "China 2050 High Renewable Energy Penetration Scenario And Roadmap Study"*

The 2015 report *China 2050 High Renewable Energy Penetration Scenario And Roadmap Study*, prepared by the Energy Research Institute (ERI) of the National Development and Reform Commission (NDRC), and funded by the Energy Foundation, presents scenario for the evolution of the Chinese energy sector that, like the CREO and LBNL studies, includes significant additional electrification, relatively modest growth in nuclear generation capacity and use, and continuing strong growth in the deployment of renewable power sources.[376] Key findings of the report, as relayed in its *Executive Summary*, include the following:

- Total power generation in 2050 is higher than that in the BAU scenario presented in section 2 of this paper, due principally to higher growth in generation in the early years of the projection, though growth in the later years (2040-2050) is somewhat lower in the ERI projection.
- The fraction of generation provided by coal-fired power plants falls from nearly 75 percent in 2011 (the base year of the ERI study) to less than 7 percent in 2050.
- The fraction of generation provided by solar and wind power rises to nearly 54 percent of the national total by 2050, with hydropower providing another 14 percent.
- Nuclear power generation capacity grows to 100 GW by 2050, at which point it supplies 4.3 percent of total generation. In the ERI projection, nuclear power's share of generation stays between 4.8 percent and 3.7 percent from 2018 through 2050.
- Carbon dioxide emissions fall to about 3 GT CO2 by 2050.
- Emissions of the local and regional air pollutants nitrogen oxides and sulfur oxides (NOx and SOx) fall to approximately 1970 levels (NOx) and about half of 1970 levels (SOx), on the order of a tenth of peak emissions of both gases (reached in 2010 and 2005, respectively).
- The average costs of generating and delivering electricity in ERI's high renewables scenario are only very modestly higher than in ERI's reference case, ranging from 0.672 RMB/kWh in 2030 to 0.685 RMB/kWh (about 10.4 US cents/kWh at current exchange rates) in 2050 in the high renewables case, "while in [the] reference scenario the average cost between 2030-2050 will stay flat around RMB 0.67/kWh".[377]
- Under the high renewables scenario, about 10 million jobs are added in the renewable energy industries between 2015 and 2050.
- Relative to the reference case, ERI's macroeconomic analysis of the high renewables scenario indicates modest changes in key economic indicators in 2050. Government spending is lower, imports and exports higher, and residential consumption up, but all within the range of a 0.23 and 1.44 percent difference between cases. Price levels in the two cases are virtually the same in 2050.

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376. Energy Research Institute (2015), *Executive Summary, China 2050 High Renewable Energy Penetration Scenario And Roadmap Study*, dated April, 2015, and available as http://www.efchina.org/Attachments/Report/report-20150420/China-2050-High-Renewable-Energy-Penetration-Scenario-and-Roadmap-Study-Executive-Summary.pdf.
377. Quote from ERI (2015), ibid. Note that projecting costs two or three decades into the future is necessarily an uncertain exercise, thus the main point here is that the costs in the high renewables case appear minimally different from those in the reference case.

Overall, ERI's results suggest that a shift to a high renewables penetration scenario can provide very significant environmental benefits at minimal overall costs to the economy—though of course some sectors will come out better than others—and without large growth in the deployment of nuclear power.

3.3 Quantitative and Qualitative Comparison of Alternative Scenarios with Baseline

The alternative scenarios of and commentary on China's near- and medium-term energy future presented above indicated that serious consideration is being given both inside and outside of China to policies to transform China's economy and energy sector towards a much lower-carbon, higher-renewables, and more efficient system than exists today. Some of the work described above (which certainly does not exhaust the universe of China energy futures studies) posit a relatively modest role for nuclear power in China's electricity sector by 2050, with little or no growth over time in nuclear's share of generation, while others suggest a more important role. In reviewing all of the projections above, and those presented in this paper, it is important to consider the breathtaking changes ongoing in the Chinese energy sector. Trends in just the past few years—marked reductions in deployment and use of coal-fired power, marked reductions in the rate of growth of electricity demand, and vast increases in wind and solar generation capacity (along with reductions in wind and solar costs) are shifting the baseline upon which scenarios are constructed. These trends may rapidly make readily achievable scenarios that look unachievable today.

Below we present, in the broader context of the overall electricity-sector scenarios described above and in section 2 of this paper, three alternative scenarios of nuclear power sector development in China, and offer a brief analysis of their relative benefits and costs, both quantitative and qualitative.[378]

3.3.1 Summary of Nuclear Capacity Scenarios

In order to explore the consequences of different scenarios of nuclear power capacity development in China, we have created three different capacity expansion cases. These are as follows:

- A "**Business as Usual**", or **BAU** case, that draws from a very recent listing of planned and proposed reactors in China prepared by the World Nuclear Association (WNA),[379] but assumes that the phase-in of new "planned" reactors will be somewhat slower than in the WNA listing,[380] and that about 55 GWe of the reactors listed as "proposed" by WNA will ultimately be built by 2050 (out of a total of 200 GWe of projects listed). Based on standard operating lifetimes, Existing LWRs are retired when they reach 40 years of service, and China's two "CANDU" reactor

378. The analysis of benefits and costs defines "energy security" in a broad sense, including traditional energy supply security and net direct costs, but also including environmental, social and political, and military-related security. For a discussion of an analytical framework used with this broader concept of energy security, see for example, David von Hippel, Tatsujiro Suzuki, James H. Williams, Timothy Savage, and Peter Hayes (2011), Energy Security and Sustainability in Northeast Asia, published in the "Asian Energy Security" Special Section of *Energy Policy* Volume 39, Issue 11, November, 2011, pages 6719–6730.

379. World Nuclear Association (2017), "Nuclear Power in China", updated July 2017, available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.

380. Some authors see evidence that China's nuclear build-out is not proceeding as rapidly as initially planned. See, for example, Steve Thomas (2016), "China's Nuclear Power Plans Melting Down", *The Diplomat*, October 29, 2016, available as http://thediplomat.com/2016/10/chinas-nuclear-power-plans-melting-down/.

units are retired after 30 years of service. By 2050, nuclear generation capacity in the BAU case reaches a level that is slightly lower than the nuclear capacity projected in the USDOE EIA's *International Energy Outlook 2017* reference case, and also slightly lower than estimated 2050 nuclear capacity the *Reinventing Fire* China Reference case.

- A "**Maximum Nuclear**" or **MAX** case, which also draws from the WNA listing but assumes a faster phase-in than in the BAU case of under-construction and "planned" units, and also assumes that about 80 percent (160 GWe) of the reactors listed in the World Nuclear Association table as "proposed" (or replacements similar in total capacity) are ultimately built and are all phased in by 2050. Existing LWRs are retired when they reach 50 years of service, so 10 years of life extension is assumed. By 2050, nuclear generation capacity in the MAX case is lower than that implied in RMI's Reinventing Fire scenario.
- A "**Minimum Nuclear**" or **MIN** case, in which the reactors listed by the World Nuclear Association as under construction or planned are all ultimately phased in by 2038, though on a much slower schedule (for those plants for which an operational date is given) than listed. After 2038, no additional plants are built, and as in the BAU case, older plants are retired as they reach the end of their standard operating lives. This lower capacity scenario could arise due to a combination of factors, including minimal growth in electricity demand in the 2030s and beyond, increased price competition from renewable energy, the availability of new and cost-effective electricity storage technologies, and/or perhaps a social backlash against nuclear power, In the MIN case, nuclear capacity begins to slowly decline about 2050, reaching a level by 2050 that is somewhat below that of the ERI and CREO scenarios described in section 3.2.

Readers should note that none of these paths account explicitly for potential shocks to the Chinese nuclear power industry, and to Chinese society as a whole, that might arise from a serious accident in a Chinese nuclear power plant. Such an event could have potentially devastating consequences for large populations.[381] The timing of such an event, should it occur, is not knowable in advance, although there is an argument that it is statistically likely over the time frame of these paths, given historical rates of major accidents per year of reactor operation.[382]

Figure 5.09 and Figure 5.10, respectively, show the capacity and electricity output implied by each of the three nuclear scenarios above. In the BAU case, capacity increases to 170 GWe by 2050, while in the MAX case capacity rises to nearly 260 GWe. In the MIN case, capacity rises to about 91 GWe by 2040 (about 260% of existing capacity as of 2017), but no new plants are added thereafter, so capacity falls to about 85 GWe by 2050 as older plants are retired. By way of comparison, as noted above, China's current (2016) overall electricity generation capacity for all types was over 1600 GW, and overall generation was nearly 6200 TWh.[383]

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381. The author of this paper prepared a rough estimate of the consequences of an incident involving (accident at or attack on) a reactor and spent fuel pool at the Ling'Ao nuclear plant in Guangdong province that suggested that "worst case" releases of Cesium-137 might result in exposures sufficient to cause hundreds of thousands of premature cancer deaths and almost certainly require the abandonment of one or several big cities, depending on the prevailing wind direction at the time of the incident (D. von Hippel and P. Hayes, 2016, unpublished).
382. See, for example, He Zuoxiu, "Chinese nuclear disaster "highly probable" by 2030," *China Dialogue,* March 19, 2013, at: https://www.chinadialogue.net/article/show/single/en/5808, and S. Wheatley, B. Sovacool, D. Sornette (2017), "Of Disasters and Dragon Kings: A Statistical Analysis of Nuclear Power Incidents and Accidents," *Risk Analysis*, Volume 37, #1, pages 99-115, available as http://onlinelibrary.wiley.com/doi/10.1111/risa.12587/epdf.
383. For electrical energy, see British Petroleum (2017), "BP Statistical Review of World Energy June 2017" workbook, available as http://www.bp.com/content/dam/bp/en/corporate/excel/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-underpinning-data.xlsx. For capacity, see, for example, "Installed capacity of electric power

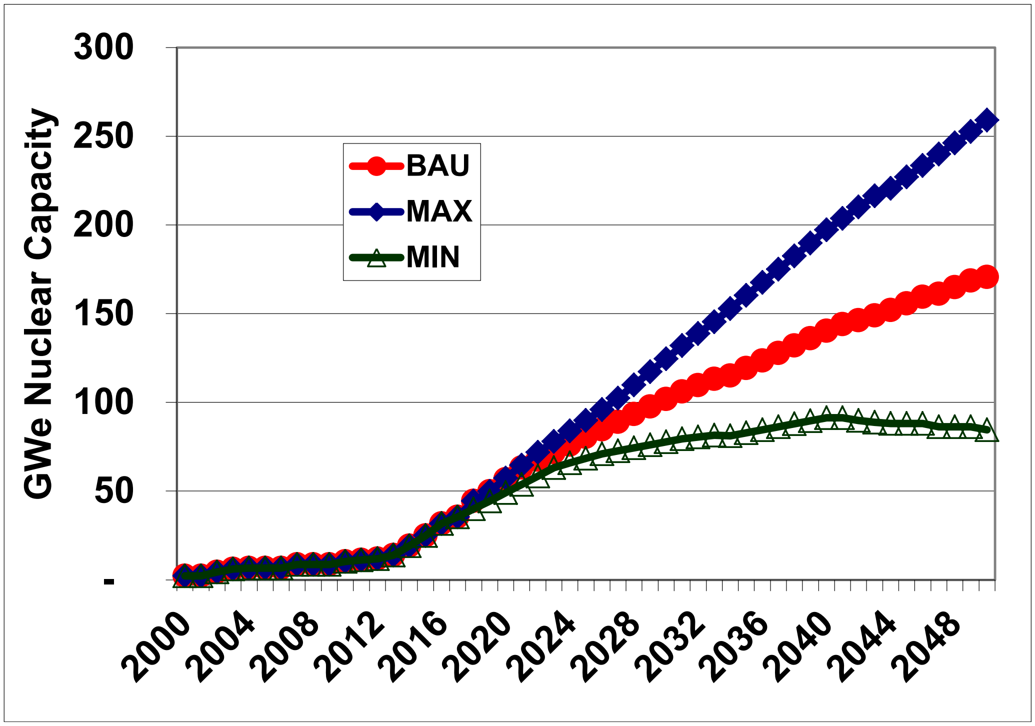

Figure 5.09: Three Scenarios of Nuclear Generation Capacity (GWe) for China through 2050

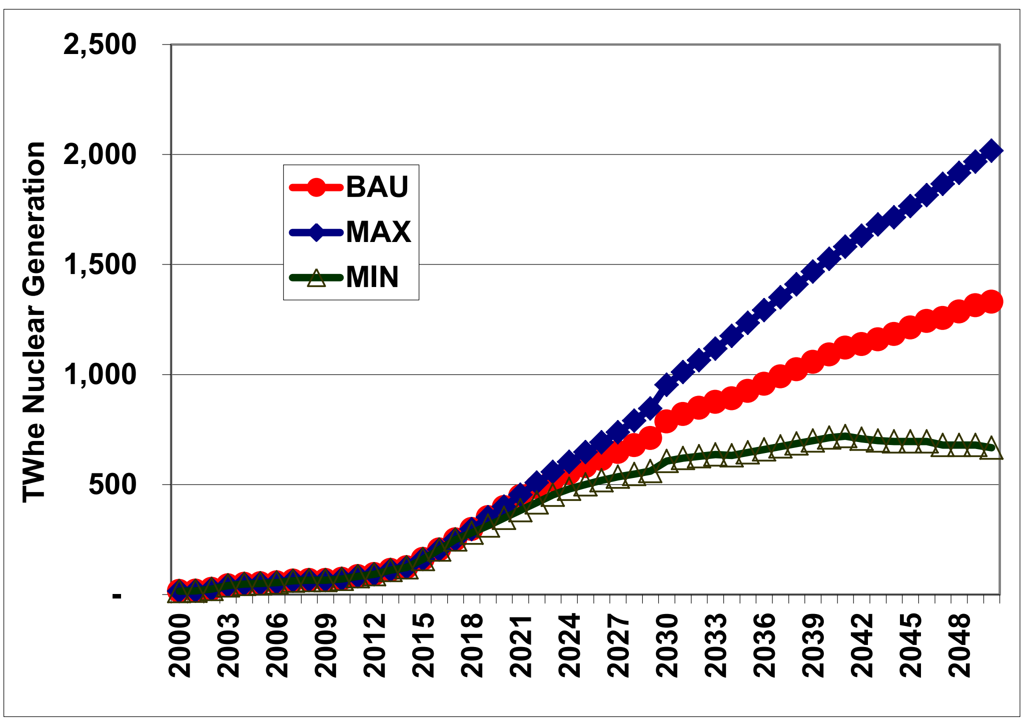

Figure 5.10: Three Scenarios of Nuclear Generation Output (TWhe) for China through 2050

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generation in China between 2010 and 2016 (in GW)", available as https://www.statista.com/statistics/302269/china-installed-power-generation-capacity/.

3.3.2 *Broader Energy and Nuclear Sectors Contexts for Nuclear Paths*

Each of the nuclear generation capacity expansion paths could, in theory, be combined with a range of different trends and policies in the broader energy and electricity sectors, as well as in the overall nuclear sector, including front-end and back-end fuel cycle developments. In practice, competition for private and public investment resources, national and societal goals and preferences, and other criteria make some combinations more plausible than others. The assumed energy and nuclear/sector contexts for each of the paths described above is as follows.

BAU Path

The BAU path is assumed to exist within a Chinese energy sector in which significant, but not aggressive, efforts to displace coal-fired power with renewable energy sources continue, energy efficiency improvements also continue, but are not major priorities of national energy policy, and some electrification of currently fossil-fuel-dominated sectors and end-uses, most notably transport, occurs, but is again aggressively pursued. In the BAU path, investment priorities in the energy sector are thus split between the nuclear and renewables sectors, with some development of coal- and gas-fired power continuing.

In the BAU path, as well as in the MAX and MIN paths as described below, China is assumed to source one-third of its uranium domestically.[384] In the nuclear sector under the BAU path, the development of uranium enrichment and reprocessing facilities, and the use of MOx fuel, proceeds roughly as described by the World Nuclear Association, but on a somewhat delayed schedule. For enrichment, this means that about 80 percent of China's enrichment needs are supplied domestically by 2020, with enrichment being entirely domestic by 2030. World (and Chinese) enrichment costs, driven in large part by Chinese nuclear expansion, follow a "medium" scenario, rising to about $75/kg SWU (about twice 2017 levels, but much lower than historical maxima) by 2050 (2009 dollars). Research and pilot development of fast reactor technologies continues, but also on a somewhat delayed schedule, such that commercialization of fast reactors is still at least several years off by 2050. MOx use is in LWRs assumed to start in 2025,[385] and 25 percent of reactors are assumed to use cores with 20% MOx fuel by 2050. Reprocessing also starts in 2025, with capacity and throughput ramping up sufficiently to process 50 percent of cooled spent fuel by 2040 and thereafter.

Spent fuel management in the BAU path, consistent with the path's emphasis on reprocessing, focuses mainly on interim spent fuel storage in spent fuel pools at reactors and at reprocessing facilities, although there is some dry cask storage of spent fuel.[386]

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384. From World Nuclear Association (2017), "China's Nuclear Fuel Cycle, updated September, 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx. "China aims to produce one-third of its uranium domestically, obtain one-third through foreign equity in mines and joint ventures overseas, and to purchase one-third on the open market."

385. See, for example, Qiang Yue, Jingke He, Laurence Stamford, and Adisa Azapagic (2017) "Nuclear Power in China: An Analysis of the Current and Near-Future Uranium Flows", *Energy Technologies*, 2017, Volume 5, pp. 681–691, available as http://onlinelibrary.wiley.com/doi/10.1002/ente.201600444/epdf.

386. "Dry casks" refers to the spent fuel storage option, used in many countries, in which cooled spent fuel is isolated in massive casks designed to last for up to 100 years. Spent fuel assemblies are typically sealed into stainless steel containers several centimeters thick, which are then placed in "overpacks" made of steel or concrete. The resulting cask is on the order of 2 meters in diameter and 6 meters tall, weighs up to 50 tons, and is essentially impervious to any significant damage that could be caused by natural disasters or accidents, as well as to all but the most determined and well-equipped attempts at penetration by criminals or terrorists.

MAX Path

Consistent with, for example, the Reinventing Fire scenario described above, the MAX Path includes both significant investments in energy efficiency and in renewable generation, as well as in electricity transmission facilities. Electrification of the energy sector is also a priority, with the reduction of greenhouse gas emissions and local/regional air pollutants a driving policy impetus. Both the savings in year 2050 electricity needs due to energy efficiency improvements and additional electrification to displace fossil fuel at the end-use level are assumed to be about half that assumed in the Reinventing Fire study—about 25 and 17 percent, respectively. The lowered assumptions for these impacts are in part due to a lower reference case assumed here than assumed in the Reinventing Fire study, and in part to an assumption that a more aggressive build-out of the nuclear sector, and of, for example, reprocessing (see below) and enrichment, will to some extent crowd out investments in efficiency and renewable energy (for example). Investment to drive the nuclear sector comes to a large extent from public funding, while renewable power investments are mostly privately driven, but take advantage of necessarily higher prices for electricity required by nuclear investments.

The MAX path focuses on building national capacity in the nuclear sector, including aggressive build-outs of uranium enrichment and related capacity, as well as reprocessing capacity and MOx use. For enrichment, this means that about 90 percent of China's enrichment needs are supplied domestically by 2020, with enrichment being entirely domestic by 2025. Enrichment costs, again driven by Chinese demand, are assumed to follow a "high" scenario, rising to $104/kg SWU (still much lower than the $160/kg SWU historical maxima) by 2050. National capacity for manufacturing of key nuclear plant components grows rapidly, and the MAX path is likely to be also combined with an aggressive national effort to export nuclear reactors to other nations. MOx use is in LWRs assumed to start in 2022, and 40 percent of reactors are assumed to use cores with 20% MOx fuel by 2050. Reprocessing on a commercial scale likewise starts in 2022, with a target of 80 percent of cooled spent fuel reprocessed by 2035. Spent fuel management focuses on interim storage in spent fuel pools at reactors and at reprocessing facilities.

MIN Path

Consistent with paths projecting high rates of renewable energy penetration in the CREO and ERI studies, the MIN path couples nuclear capacity expansion at a rate that holds the nuclear share of generation roughly constant with aggressive development of renewable energy for power generation and for end-uses, plus aggressive energy efficiency programs. Electrification is also an emphasis, both for greenhouse gas emissions reduction and to bring down emissions of local and regional air pollutants. Energy efficiency efforts, and the use of more renewable energy sources at the end-use level, are assumed to reduce electricity needs by 33 percent by 2030 relative to BAU requirements, with electrification adding 20 percent back to electricity demand by 2050. Ongoing policies, including carbon markets and carbon taxes, preferentially target markets for renewable energy and energy efficiency, with the proceeds used to support investment in both, as well as in pollution control and environmental remediation. The MIN path does not explicitly include carbon capture and sequestration (CCS) for coal- and/or gas-fired power plants, as used in the "IPCC Target" scenario of the Gang He, et al (2016) study referenced above, but could include CCS if CCS technology is suitably advanced and if greenhouse gas emissions reduction policies in China required its use. China has been rapidly developing facilities for importing LNG, and LNG could play a more important role in power generation in China's future in a variant of a MIN path, with or without CCS. Greater gas-fired generation, perhaps displacing some planned nuclear plants, would be even more plausible if, for example, infrastructure for bringing North American gas to China at attractive prices can be developed. Also not explicitly modeled in the MIN path is the development and widespread use of electricity storage technologies, which would be needed to complement the aggressive development of renewable (wind and solar) electricity sources.

In the nuclear sector, reprocessing is not pursued beyond the existing and under-construction pilot plants, and MOx use in existing reactors is limited. Uranium enrichment facilities planned for the near-term are built by 2025, but no additional enrichment plants are built, and the remainder of China's required enrichment services are imported. With a smaller nuclear capacity expansion in China, and (assumed) reduced nuclear restarts in Japan, relative to other scenarios, international (and Chinese) enrichment costs follow a "low" trajectory, reaching $54/kg SWU by 2050, about 40 percent above 2017 levels. Efforts to export reactors continue, but are not heavily subsidized by the Chinese government. Research into fast reactors continues, but at a low level, and commercialization of fast reactors is still decades away by 2050. In part to provide fuel for fast reactor research, the smaller (200 tHM/yr) reprocessing facility reportedly (as of 2017) being built at Gansu is eventually completed, but is not run until 2025, and then at only partial capacity for several years. Pu from this facility is used to produce MOx fuel, which is used in 10 percent of LWRs by 2050, with phase-in occurring slowly starting in 2030. MOx fuel again makes up 20 percent of reactor cores in those units that use MOx. Cooled spent fuel is stored mostly in a mixture of at-reactor spent fuel pools and in dry casks, which may be located at or near reactors or at a centralized dry cask facility.

3.3.3 Flows of Nuclear Materials

Table 5.02 shows estimated total requirements for uranium and uranium ore in each of the three scenarios, both for the individual years 2010, 2030, and 2050, and on a cumulative basis from 2015 through 2050. The MAX path implies the use of over 50,000 tons of U annually by 2050, while less than a third as much is required in the MIN path. The extraction of 11 million tons of ore is required by 2050 in the MAX path, but placed in context, this is much less than a percent of the total volume of coal extracted to fuel China's power sector. By assumption, two thirds of Chinese uranium needs are sourced abroad, and one third are from domestic mines.

Table 5.02: Uranium Requirements by Nuclear Capacity Expansion Path

Parameter	YEAR	MAX Path	BAU Path	MIN Path
Annual Total Metric Tons Natural Uranium (as U) Imported plus Domestic Production	2010	2,629	2,629	2,629
	2030	27,718	21,837	15,946
	2050	53,659	35,106	16,570
	Cumulative, 2015-2050	1,105,629	820,318	540,581
Annual Total Thousand Metric Tons Uranium Ore (from In-country and outside mines) to Supply All Domestic Uranium Needs	2010	546	546	546
	2030	5,752	4,532	3,309
	2050	11,136	7,286	3,439
	Cumulative, 2015-2050	229,457	170,245	112,190

Under the MAX expansion path, if China chose to provide all of its own enriched uranium, China alone would need to build new enrichment capacity by 2050 approximately equal to more than half of today's global capacity. China's annual requirement requirements by 2050 rise to nearly 42 Million kg SWU. Under the MIN expansion path, however, international enrichment facilities extant as of 2015 are likely sufficient to meet China's enrichment needs by 2050 (about 12 million kg SWU), even factoring in likely East Asia regional and out-of-region demand without significant expansion, assuming existing international enrichment facilities (or replacement facilities) continue to operate. Though the ROK and Japan have accounted for almost all enriched uranium in East Asia needs pre-Fukushima, the rapid growth of China's nuclear power sector and the slow process of restarting Japan's reactors means that China's demand for enrichment will likely outstrip needs in the rest of the region well before 2020.

The uranium oxide (UOx) and MOx fuel requirements under each scenario are summarized in Table 5.03. MOx fuel requirements in the BAU path by 2050 are less than half of those in the MAX path, and MIN path MOx use is less than a tenth of MAX path use by 2050.

Table 5.03: Requirements for UOx and MOx Fuel in Each of 3 Nuclear Paths

Parameter	YEAR	MAX Path	BAU Path	MIN Path
Implied Total Requirements for UOx Fuel (excluding MOx) from All Sources (Metric tonnes heavy metal in fabricated fuel)	2010	267	267	267
	2030	2,929	2,327	1,711
	2050	5,417	3,620	1,763
	Cumulative, 2015-2050	115,040	86,601	57,961
Implied Requirements for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	-	-	-
	2030	60	24	-
	2050	408	191	36
	Cumulative, 2015-2050	4,657	2,123	394

With widely varying use of reprocessing in the three scenarios, it is not surprising that plutonium production and uptake (as MOx) also is significantly different, as shown in Figure 5.11. Cumulative plutonium separation through reprocessing rises to over 450 tons of Pu in the MAX case by 2050, and about 9 tons of Pu inventory remains after MOx use in 2050. About 200 tons of Pu are produced by 2050 in the BAU case, but almost all stocks are used as MOx. In the MIN case, only about 27 tons of Pu are produced via reprocessing in China through 2050, and more than that amount of Pu is used as MOx, implying, for example, that some Pu from other nations (stocks from Russia, the UK, or France) is blended into fuel used in Chinese reactors, and/or military Pu from the Chinese weapons program is disposed of as MOx. Note that all of these calculations of net Pu inventories by 2050 are extremely sensitive to the combination of assumptions regarding the fraction of spent fuel reprocessed and the amount of fuel used as MOx. In practical terms, this means that if a reprocessing program is successful BUT MOx use is delayed, significant inventories of Pu can build up, and can serve as a proliferation target. As a sensitivity analysis, Figure 5.11-12 shows what might happen if reprocessing proceeds in each path as indicated above, but MOx use is delayed by 10 years in each path, and used in only half as many reactors—a plausible outcome given the difficulties in implementing MOx use that other nations have experienced to date. In this sensitivity case, inventories of Pu of about 300, 140, and 18 tons build up in the MAX, BAU, and MIN cases, respectively, by 2050, at which point Pu stocks are still continuing to accrue. The stocks building up in this sensitivity case in the MAX and BAU paths would suffice to build tens of thousands of nuclear weapons, and even the MIN case stocks represent thousands of times the mass of Pu contained in a nuclear warhead. Additionally, paths that produce high volumes of Pu, whether or not fully consumed as MOx, would tend to enhance the chance of significant volumes of Pu going astray, as the more Pu is produced, the easier it will be for weapons-relevant quantities (kilograms) of Pu, amounting to less than a tenth of a percent of MAX and BAU annual output from reprocessing facilities, to be diverted for criminal purposes.

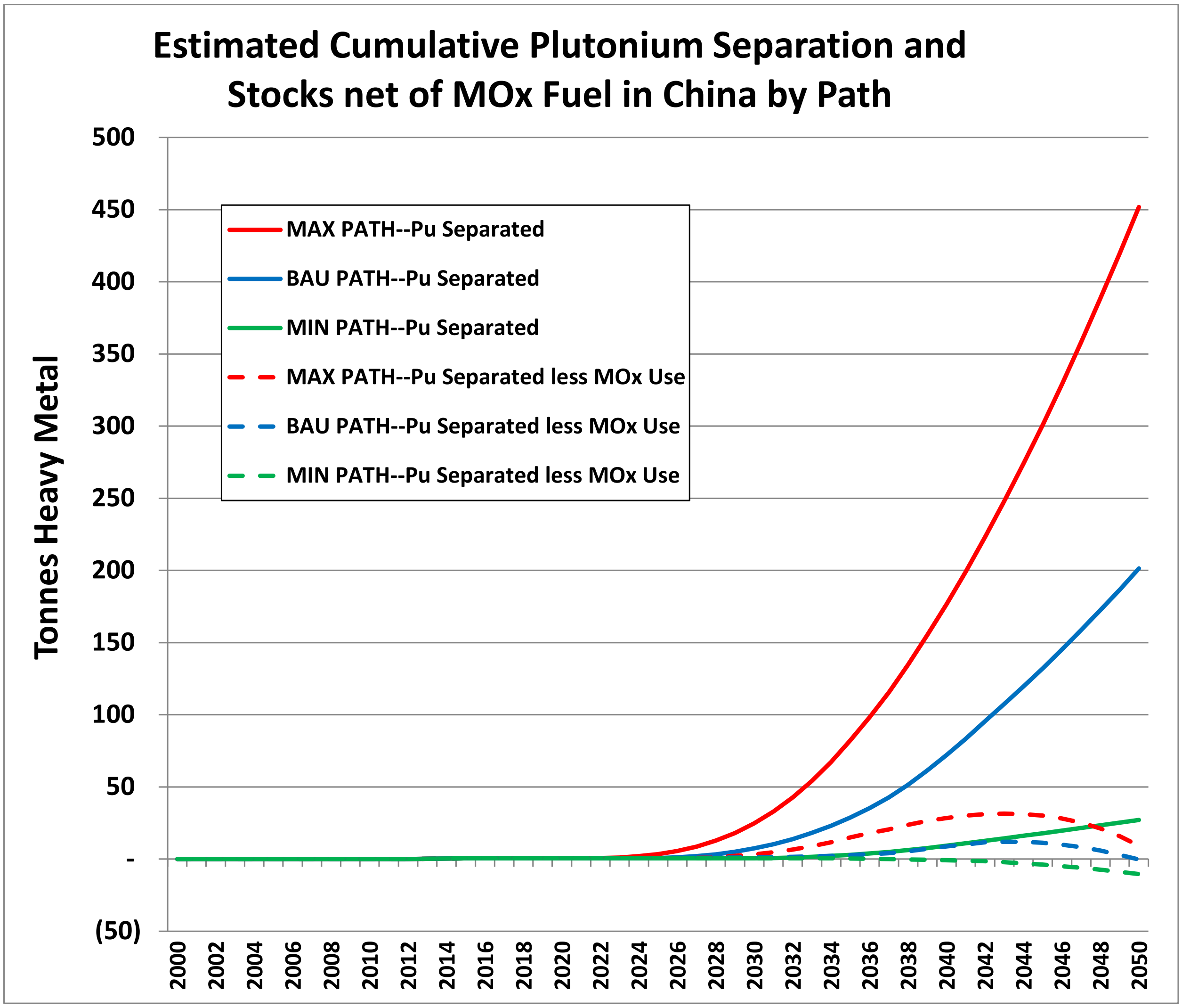

Figure 5.11: Pu Separation and Stocks Net of MOx Fuel Use by Path

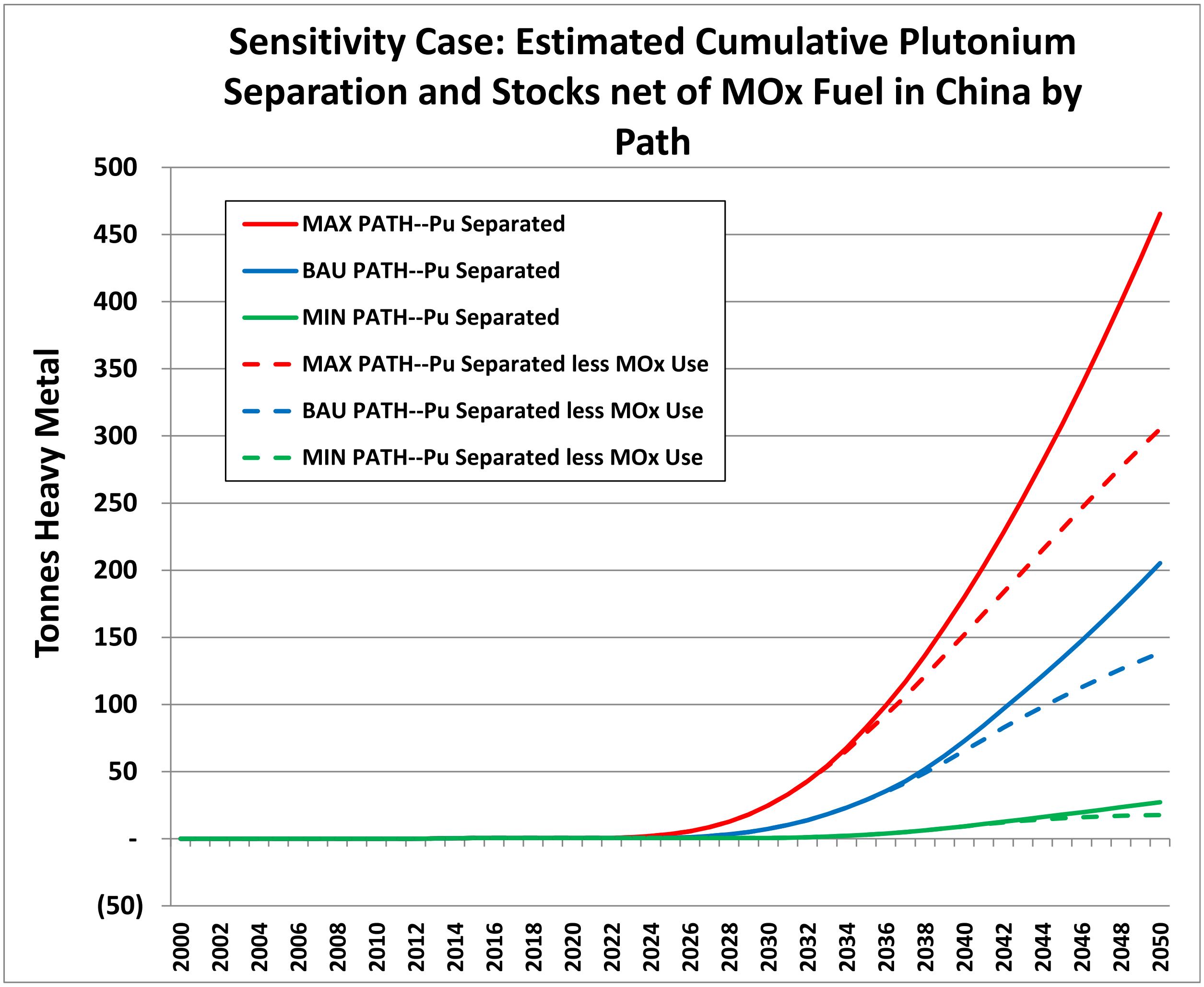

Figure 5.12: Sensitivity Analysis: Pu Separation and Stocks Net of MOx Fuel Use by Path if MOx Use is Delayed

Table 5.04 presents annual and cumulative results for the production of cooled spent fuel[387] and high-level wastes from reprocessing, as well as the number of casks used for dry cask storage, in each of the three nuclear paths. Despite the large difference in 2050 nuclear generation capacity between the three paths, the cooled spent fuel produced over time is not all that different, because cooled spent fuel production lags changes in generation. The MAX scenario produces much more high-level waste (HLW) from reprocessing than the other cases. Though the volume of HLW is not large—5000 or so cubic meters could be contained in 25 or so average urban apartments—it is highly radioactive and, like spent fuel, remains so for thousands of years, meaning that special well-secured facilities capable of holding the wastes indefinitely

387. Spent LWR nuclear fuel must be cooled—typically for five to 10 years, in spent fuel pools before it can be either reprocessed, placed in dry casks for long-term (100 years or more) storage, or placed in long term storage/indefinite or permanent disposal in mined repositories, such as the canceled Yucca Mountain facility in the U.S., or in deep borehole disposal (a technology in the early phases of development—see, for example, Neil Chapman (2013), "Deep Borehole Disposal of Spent Fuel and Other Radioactive Wastes", NAPSNet Special Reports, July 25, 2013, https://nautilus.org/napsnet/napsnet-special-reports/deep-borehole-disposal-of-spent-fuel-and-other-radioactive-wastes/.

must be constructed. In the MIN path, where the emphasis is on dry cask storage, on the order of 2600 casks would be required to accommodate the cooled spent fuel produced by 2050, not including the relatively small amount of spent fuel reprocessed in the MIN path. To put this number of casks in perspective, the total dry casks filled during the MIN path could be stored in an area of less than 10 hectares, just a bit bigger than area enclosed by the fence around the White House in Washington DC.

Table 5.04: Spent Fuel Management Results for Three Nuclear Paths

Parameter	YEAR	MAX Path	BAU Path	MIN Path
Annual New Spent LWR Fuel Cooled and Available for Reprocessing, Storage, or Disposal (excluding MOx spent fuel), Metric Tonnes Heavy Metal	2010	51	51	51
	2030	1,190	1,139	975
	2050	3,654	2,686	1,747
	Cumulative, 2015-2050	57,028	46,688	35,880
Annual Spent MOx Fuel Cooled and Available for Storage or Disposal, Metric Tonnes Heavy Metal	2010	-	-	-
	2030	-	-	-
	2050	239	112	23
	Cumulative, 2015-2050	2,020	883	150
Implied Amount of Spent LWR Fuel (UOx only) Reprocessed in Total for Use in Domestic Reactors (Metric tonnes heavy metal)	2010	1	1	1
	2030	612	214	9
	2050	2,923	1,343	175
	Cumulative, 2015-2050	41,045	18,276	2,438
Implied Volume of High-level Waste (as vitrified) from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0.15	0.15	0.15
	2030	70.37	24.57	1.02
	2050	336.18	154.47	20.10
	Cumulative, 2015-2050	4,720.15	2,101.75	280.35
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Net of Reprocessing (units)	2010	-	-	-
	2030	-	-	-
	2050	36	109	156
	Cumulative, 2015-2050	362	1,496	2,608
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (units)	2010	-	-	-
	2030	-	-	-
	2050	24	11	2
	Cumulative, 2015-2050	202	88	15

3.3.4 Costs

Although a full quantitative evaluation of the direct costs of the scenarios described above is beyond the scope of this paper, some of the considerations in comparing the costs between the three scenarios in qualitative terms are as follows:

- Fossil fuel costs for electricity generation will be highest for the BAU case, with annual costs in the MAX case about half of BAU levels by 2050, and in the MAX case about a quarter of BAU levels, due to displacement of fossil fuels by efficiency improvements, electrification, and use of renewable energy for direct end-uses and electricity generation.

- Overall fossil fuel costs, including “upstream” costs for oil refining, coal mining, and other fuel-cycle activities, will be lower due to electrification of end-uses in the MAX scenario, and even lower in the MIN case.

- There is likely to be very little growth in capital and operating and maintenance (O&M) costs for fossil-fueled power plants in any of the scenarios, though these costs will be lower in the MAX path, and lower still in the MIN path, as more coal-fired generation is displaced by nuclear (in the MAX path) and renewable generation/energy efficiency in both paths, In the MAX and especially the MIN path, at least more coal-fired capacity will likely be retired, providing a reduction in O&M costs. One factor that could cause power plant costs to rise, and could be applied to any of the three scenarios, is if more stringent controls are required to reduce local and regional air pollutants, and/or if carbon capture and sequestration is required on fossil-fueled plants.

- Costs for energy efficiency and increased deployment of end-use renewables will be higher in the MAX case than in the BAU case, and higher still in the MIN case, although previous experience in China and elsewhere suggests that in many cases energy efficiency provides electricity savings more cheaply than electricity case be generated by supply-side resources. Thus when the avoided costs of electricity generation and direct fuel use are factored in, efficiency investments will likely yield a net savings in overall direct costs. The much higher rate of renewables deployment in the MIN path will likely reduce the per-unit costs of renewable energy systems, and accompanying electricity storage systems. It is difficult to say whether the net costs of aggressive deployment of energy efficiency and renewable energy in the MIN path will be higher or lower than the costs of the conventional and nuclear energy systems that they displace in the BAU and MAX paths, but recent experience and at least some previous studies of energy futures suggest that the cost differences may be small relative to overall energy system costs and to the uncertainties of costs projected three decades into the future.

- The MAX scenario will have the highest overall costs for nuclear generation capacity, as well as for fixed and non-fuel variable operating and maintenance (O&M) costs, followed by the BAU case. MIN case total capacity costs and O&M will be substantially lower than in the other two cases. Costs for fast reactor research and development will be highest in the MAX case, and relatively limited in the MIN case.

Nuclear fuel cycle costs—exclusive of reactor capital and non-fuel O&M costs—have been quantified for each of the three nuclear paths described above. Not surprisingly, as shown in Figure 5.13, Nuclear fuel cycle costs are much higher in the MAX path, at a about $560 billion on a cumulative basis over 2015 through 2950. This total is nearly twice as much as for the BAU path, and on the order of five times that of the MIN path. The three largest cost categories are raw uranium and uranium enrichment—higher in the MAX path due to higher cost escalation assumptions—and reprocessing costs, which are nearly avoided altogether in the MIN path.

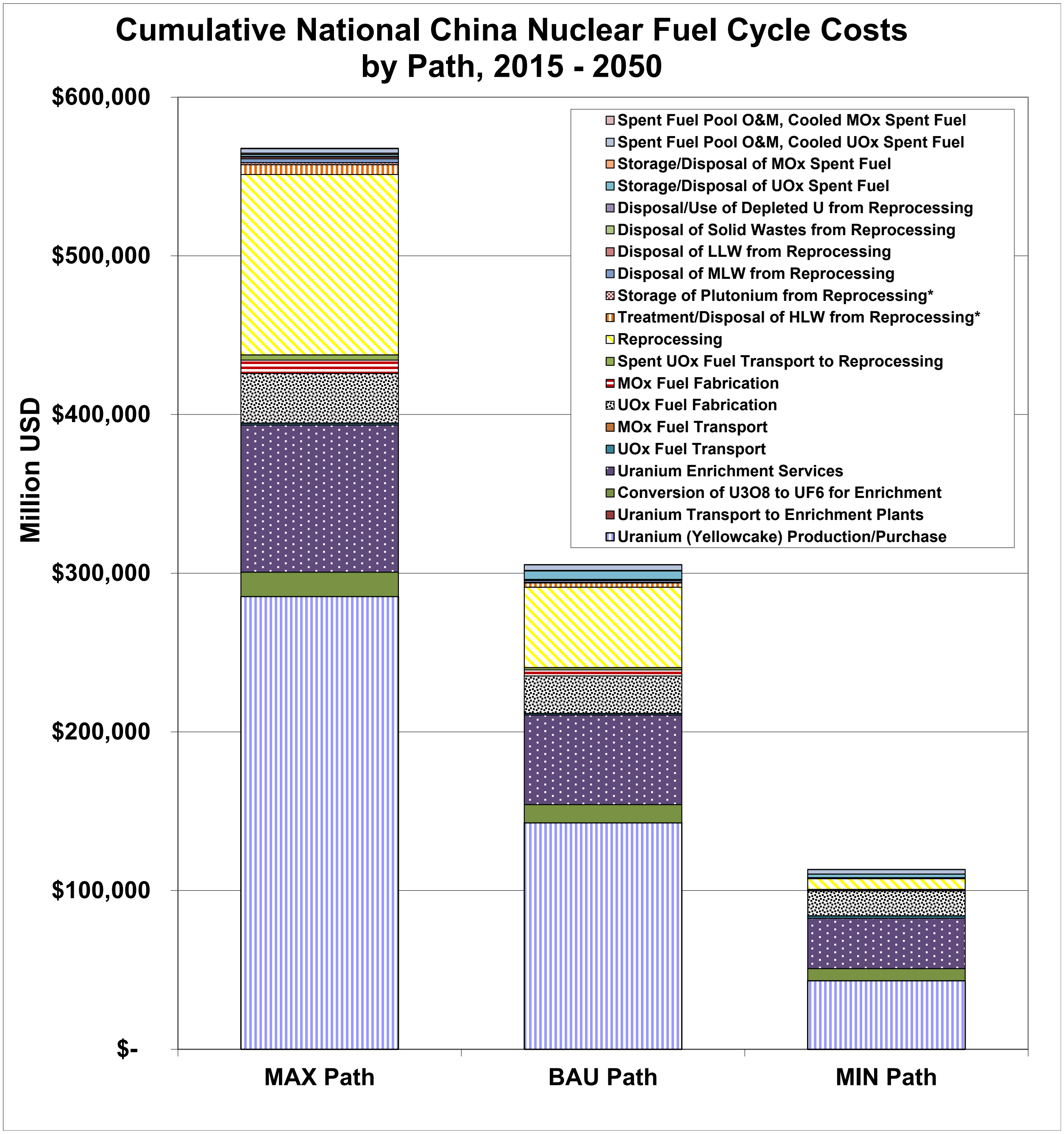

Figure 5.13

The relative indirect costs to the economy of alternative energy scenarios, and the policies that will drive them, are often a key consideration for policymakers. The perceived and projected impacts of different nuclear scenarios on, for example, GDP and employment at the provincial and national levels in China will have a considerable impact on the acceptability of particular scenarios and policies. In practice, there are always winners and losers—for example, with regard to employment in different sectors and even regions—when policies are shifted, but the net impact of these changes is very hard to know in advance, due to policy- and non-policy-related shifts in the economy and technology (and in underlying costs and factor prices) shifts over time, and to the general uncertainty associated with any economic prognostication. In many macroeconomic studies of different energy scenarios, changes to GDP and employment by, for example, 2050 come out looking like large numbers, but are invariably swamped by the underlying combination of the size of overall GDP by a target year, and the uncertainties inherent in the analysis.

That said, there will be certain sectors that will doubtless win and lose to different extents between the three nuclear scenarios. The nuclear sector, and particularly firms and government organizations associated with advanced fuel cycles and reprocessing, will be the losers in the MIN scenario, and to a lesser extent, the BAU case, relative to the MAX scenario, while the renewable energy industries will benefit most in the MIN case. Coal mining income and employment will be reduced substantially in the MIN case relative to the other cases, though coal mining in China is becoming less labor-intensive in general, following the historical trend in the US and other places. In general, many studies have found that scenarios that focus on renewable energy and energy efficiency produce more long-term jobs and similar if not greater national and regional net income than scenarios focused on supplies of conventional and nuclear energy, but, as noted, there will inevitably be subsectors and industries that are winners and losers in any case relative to any other.

3.3.5 Energy Supply Security

The traditional concept of energy supply security, in brief, is that the more a country can source its fuel requirements from its own territory—or failing that, the more a country can draw for its energy needs from a diversity of domestic resources and imports from large number of trading partners—the more energy supply security is enhanced. Under that definition, the MAX case, which uses more nuclear power and less oil (the reduction being mostly due to electrification of the transport and other sectors) coal, and natural gas, is provides arguably more energy security than the BAU case. The MIN case, with more use of domestic resources (wind, solar, and energy efficiency) than the other two cases, arguably comes out on top in terms of energy supply security. Figure 5.14 shows the relative use of fossil fuels, both cumulative and for selected years, under each case. By assumption, in each case, uranium is sourced from the same ratio of domestic and foreign sources, though in principle, a higher proportion of domestic U could be used in the BAU and, especially, the MIN cases, given the lower overall U requirements.

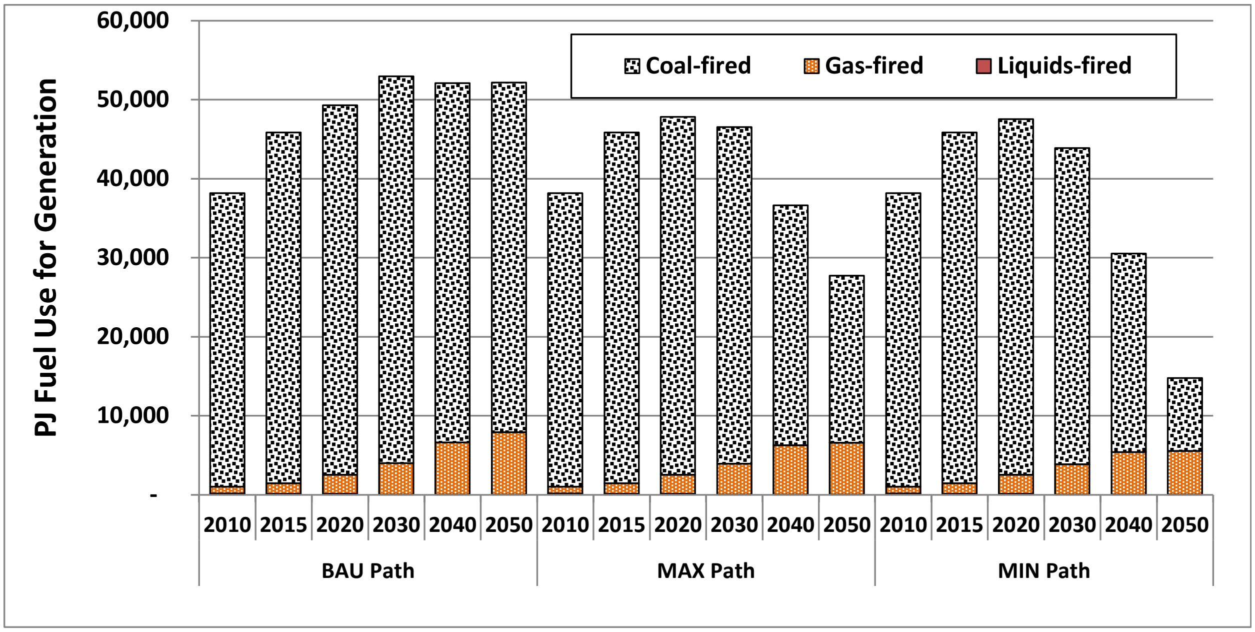

Figure 5.14: Annual Fossil Fuel Use for Electricity Generation by Type and Year for Three Paths

3.3.6 Environment

The environmental component of a broader concept of "energy security" includes comparing the performance of the three scenarios on the basis of emissions of greenhouse gas emissions, local and regional air pollutant production, water pollution, and disposal of nuclear-fuel-cycle related wastes. With respect to these criteria, the three nuclear paths described above yield the following quantitative and qualitative comparisons:

- The MIN path produces nearly 30 percent lower cumulative electricity generation sector (2015-2050) greenhouse gas emissions than the other BAU path, and in particular, as shown in Figure 5.15, produces a small fraction of the year-2050 emissions included in the BAU and MAX paths. Although the overall Chinese societal GHG emissions are the main concern here, and have not been quantified for this paper, the inclusion of additional electrification in the MAX path indicates that China's MAX-path GHG emissions will be considerably lower than in the BAU path, and emissions in the MIN path will be lower still.
- Likewise, though not directly quantified here, non-GHG air pollutant emissions of consequence to local and regional air quality will be less in the MAX path than in the BAU Path, with emissions in the MIN path considerably less in the other two cases, particularly by 2050.

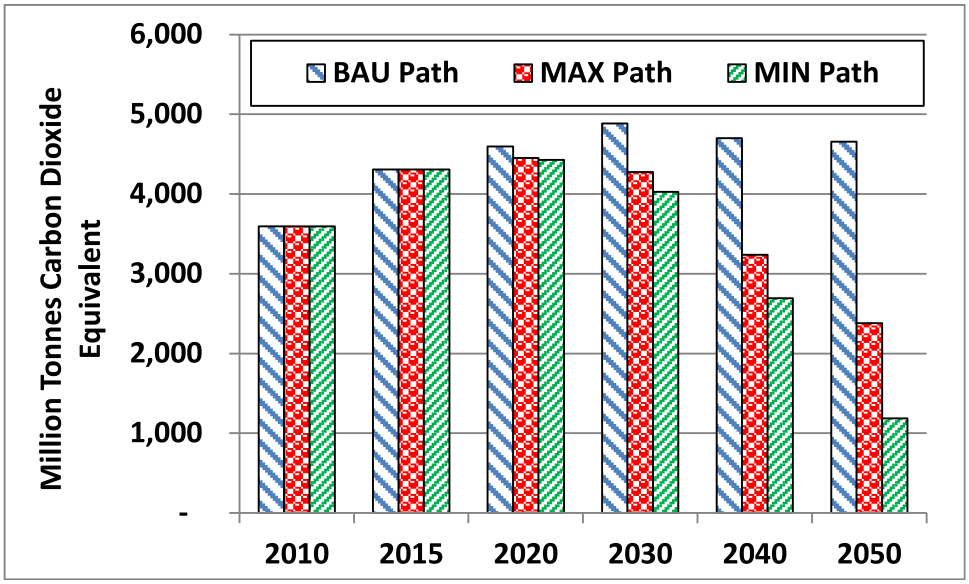

Figure 5.15: Greenhouse Gas Emissions from the Electricity Generation Sector in China Under Three Nuclear Power Development Paths

- Because considerably less coal is used in the MIN and MAX paths than in the BAU path, water pollution from coal mines will be less in those paths. Thermal pollution from coal-fired power plants will also be less, though additional thermal pollution from nuclear power plants, some of which may be on inland sites (on rivers), may occur in the MAX path, relative to the other two paths. Additional water pollution and solid wastes from uranium mining in China and abroad will accrue in the BAU and, especially, MAX paths relative to the MIN path.
- The disposal of nuclear-sector-related waste streams will be much more of an issue in the BAU and, especially, MAX paths relative to the MIN path. Considerable HLW and intermediate and low-level wastes from reprocessing will accrue in the BAU and MAX paths, and China will need to find a final resting place for those materials, as well as for any spent fuel placed in long-term storage/disposal. Finding places to store/dispose of these materials may prove to be foci for political and social problems, as noted below.

3.3.7 Social and Political Criteria, and Military Security

During China's period of rapid economic growth, Chinese decisionmakers have typically given (or at least, exhibited) limited concern to the reaction of local populations in decisions on siting of key energy-sector facilities, relative to decisionmakers in many Western nations. Over the past decade, however, trends have suggested that the role of Chinese civil society in the siting of large and potentially polluting or dangerous facilities has been growing, at least in some ways. Very recent events have arguably suggested that civil society's voice in China may not continue to develop as some in the West might have hoped, though the impact of recent changes in Chinese governance on the nuclear sector is not yet clear.[388] In general, paths,

388. See, for example, Chris Buckley and Adam Wu (2018), "Ending Term Limits for China's Xi Is a Big Deal. Here's Why",

like the MAX path, that call for large, centralized, secure facilities for handling and managing nuclear materials may galvanize opposition to such facilities on the local and national levels, thus making those paths arguably less secure than paths like the MIN path, where energy needs are supplied by resources that are often tapped by facilities that are more distributed and each smaller and less obtrusive (and polluting) than the other two paths.

Additionally, the nuclear facilities (including enrichment and reprocessing, nuclear power plants, and spent fuel transport) that are part of the BAU and, particularly, the MAX paths will require much more in the way of military security arrangements than the MIN path. These military security requirements increase military costs and enhance the possibility of conflicts between the military security apparatus and a population becoming accustom to greater social and economic freedoms. The impact of required nuclear sector security arrangements will be mirrored, to some extent, by the greater needs to secure supplies of oil and oil transport lanes; the needs to secure oil supplies will be highest in the BAU case.

4 Conclusions

4.1 What Alternative Scenarios of China's Nuclear Future Tell Us

As of 2017, China arguably sits at a point of decision, inflection, or possibly both in the evolution of its electricity generation system, its nuclear power future, and possibly its energy sector as a whole. Scenarios of nuclear power development in China, including those presented in this paper and many others, span the range from modest growth to 80-100 GWe by 2050 (from about 34 GWe today) to projecting growth to 300 to 400 or more GWe of nuclear power by 2050, with the beginnings of commercialization of fast reactor technologies. At the same time, transitions are occurring for China's coal-fired power fleet, with plans for future new capacity being rapidly scaled back, and smaller, less-efficient units being taken out of service. The rethinking of plans for expansion of coal-fired power is in part in response to progressively more stringent policies to address local and regional air pollution, but also in response to the two trends, particularly in recent years, of accelerating deployment of wind and solar power, and reduced growth in electricity demand, the latter particularly in comparison to the double-digit growth rates of recent decades.

Developing internally-consistent scenarios of China's electricity sector in general, and the nuclear energy sector within the electricity sector, with the different scenarios designed to serve the same needs for energy services in similar economic futures, provides a means to test policy directions. China could choose a path including rapid deployment of LWRs with spent fuel reprocessing, blending the resulting plutonium into MOx fuel and subsequent use of same in LWRs and, ultimately, in a fleet of fast reactors. Or an explicit or implicit policy (for example, through adjusting levels of power sector subsidies) could damp down the current nuclear build-out after those reactors currently under construction are built, such that additions in the decades after 2025 are modest, while aggressively encouraging energy efficiency and the development of solar and wind power, plus the supply-side changes (transmission systems, smart grids, and electricity storage, for example) that would be needed to maximize renewable energy usability. The estimates of future fuels use, costs, pollutant and waste emissions, and accompanying (typically) qualitative consideration of issues such as the relative political and social security ramifications that result from consideration of different future scenarios provide a way of testing and illustrating for policymakers the different ways

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The New York Times, March 10, 2018, available as https://www.nytimes.com/2018/03/10/world/asia/china-xi-jinping-term-limit-explainer.html.

of organizing the energy future of a nation.

4.2 Prospects for Meeting China's Future Energy Needs with Limited *or no* Increases in Nuclear Capacity and Proliferation-resistant Fuel Cycles

The comparison of the BAU, MAX, and MIN paths for the Chinese nuclear and electricity sectors, considered together with the existing body of China scenarios work described (in part) in section 3.2 of this paper, suggests that it will be possible for China to meet its economic development, GHG and air pollutant emissions reduction, and other goals without an extended and massive build-out of LWR capacity, and without expansions of uranium enrichment or reprocessing capacity beyond those projects now underway. Further, although the MIN case implies that China will not become a major exporter of nuclear power technologies, it also implies that China will continue along its current trend of being perhaps a dominant provider of renewable power systems. Nuclear sector costs in the MIN Path are much lower, both on an aggregate basis and per unit of output, than in the other two paths, largely because of lower uranium, enrichment, and reprocessing costs. Although these costs are only a small part of the overall cost of providing energy services to the Chinese economy, indications from past experience and other studies is that the emphasis on energy efficiency and renewable energy will offer the opportunity for China to effectively address its environmental concerns without significant (if any) additional costs, relative to a reference path. Further, a path with less nuclear power and fewer front-end and back-end nuclear facilities will be arguably easier to deploy in a social and political sense, particularly as expectations for a stronger voice in how its future unfolds continue to grow among the Chinese citizenry.

The MIN scenario provides significant benefits over the other two cases in terms of plutonium production and stocks (transient and otherwise), and thus provides significantly lower risk of the proliferation of nuclear weapons. For the MIN path to become a reality, policy support for energy efficiency and renewable energy will need to take precedence over policy support for nuclear power. Trends in recent years, including the slow-down in reactor construction and re-thinking of nuclear safety regulations post-Fukushima, ongoing structural change in the Chinese economy away from heavy industry (and much-reduced growth in electricity needs), and exceedance of even the ambitions government targets for renewable energy all point toward the enhanced practicality of a low-nuclear path for the evolution of the Chinese energy sector. Acknowledgement of the benefits of the MIN path (or similar) for China by international political and trading partners, probably including international policies that encourage such a path and embracing energy paths of their own that de-emphasize nuclear power, enrichment, and reprocessing, would likely serve to encourage China to move toward a low-nuclear future.

China arguably is at a point in marketing its nuclear technologies abroad in which its technologies are not particularly competitive—as they are based on older US and other Western designs—and it is facing a worldwide market for nuclear power that even a Russian reactor vendor has reportedly described as weak. If China's domestic market for nuclear power were to follow a trajectory more like the MIN path described above than the BAU or MAX paths, it seems likely that China's nuclear exports would be relatively de-emphasized. Building and maintaining the capabilities to export nuclear technologies, including to countries where nuclear weapons proliferation is a danger (or historical fact, as in Pakistan), will be technically and economically riskier and more difficult without a burgeoning domestic market to fall back on. As such, timely encouragement (including by example) of China by the US and the rest of the international community to focus on non-nuclear technologies for power generation could contribute to influences already in play and induce China to focus its efforts on exporting technologies that do not carry a weapons proliferation threat.

Appendix A

Can the IAEA Safeguard Fuel-Cycle Facilities? The Historical Record

November 2014

Alan J. Kuperman, David Sokolow, Edwin S. Lyman

Introduction

The peaceful use of nuclear power is premised on an international ability to prevent bomb-grade nuclear materials from going missing from civilian fuel-cycle facilities. This depends crucially on "safeguards" ad- ministered by the International Atomic Energy Agen- cy (IAEA), which are supposed to detect any clandestine removal of a bomb's worth of fissile material (or more) in time to prevent it from being manufactured into one or more nuclear weapons. Unfortunately, more than 4 decades after the creation of IAEA safeguards, considerable doubt remains as to whether the agency can attain this goal even at the relatively small number of existing fuel-cycle facilities, let alone at the many more such facilities envisioned as nuclear power expands globally.

Accordingly, this chapter assesses the current and anticipated efficacy of IAEA safeguards at civilian fuel-cycle facilities (also known as "bulk handling facilities") and then formulates policy recommendations. The chapter starts by detailing the empirical record of safeguards shortfalls at such facilities. Second, it explains the two major risks of clandestine removal of fissile material from fuel-cycle facilities: diversion by states, or theft by substate insiders. Third, it details the scope of such facilities worldwide. Fourth, the chapter discusses the technical and political obstacles to achieving safeguards objectives, and various proposals to overcome them. Finally, the chapter concludes with policy recommendations based on the current and projected capabilities of IAEA safeguards.[389]

Empirical Record

Nuclear fuel-cycle facilities around the world, in states with and without nuclear weapons, have suffered accounting discrepancies entailing many bombs' worth of fissile material. This section first explores the record at such facilities in two nuclear-weapons states: the United Kingdom (UK) and France. Second, it illustrates the inadequacy of accountancy at such facilities under IAEA safeguards in two countries with varying levels of cooperation with the agency: Japan and Iran.

389. This chapter draws upon a previously published chapter. See Edwin S. Lyman, "Can Nuclear Fuel Production in Iran and Elsewhere Be Safeguarded Against Diversion?" Henry Sokolski, ed., *Falling Behind: International Scrutiny of the Peaceful Atom*, Carlisle, PA: Strategic Studies Institute, U.S. Army War College, 2008, pp. 101-120.

United Kingdom.

British Nuclear Fuels Limited's (BNFL) Sellafield site in northwest England includes a mixed-oxide (MOX) fuel facility, which operated from 2001 to 2011, as well as the Thermal Oxide Reprocessing Plant (THORP) that continues to operate. In 2005, an audit of the nuclear materials at the MOX facility revealed that the "material unaccounted for" (MUF) was 29.6 kilograms (kg) of plutonium, or roughly 3.5 "significant quantities" (SQ) of this fissile material, enough for several nuclear weapons. BNFL insisted that the figure did not mean that any material had been re- moved without authorization from its plants. The company asserted that its techniques to account for nuclear material followed internationally approved and recognized best practices. In particular, BNFL contended that the systems of statistical measurement and control at THORP were "the most advanced in the world."[390] However, on May 9, 2005, a BNFL inquiry revealed that a massive leak at THORP had gone undetected for 9 months. The leak occurred in a feed pipe to one of the two accountancy vessels, resulting in accumulation of 83.4 cubic meters of dissolver solution. This solution contained an estimated 19 metric tons of uranium and 190-kg of plutonium.[391] An accountancy tank is where the initial inventory of fissile material is measured for the purpose of establishing shipper receiver differences (SRD). But the system failed to detect the increasing loss of material until 8 months after it began. To the credit of the plant's material accounting system, the first indications of the problem came not from any safety detectors (several of which were malfunctioning), but from the company's Safeguards Department, when it observed an anomalous SRD in March. Despite that, the leak was not uncovered until a month later.

In BNFL's review of the incident, the company commended the role of its Safeguards Department in detecting the leak, although acknowledging that the Nuclear Materials Accountancy system had not provided timely warning of lost material. The system "is intended to provide overall accountancy balances," and "is not designed to (nor is it intended that it should) be responsive to track material on a more real time basis." Later, BNFL recommended the introduction of "a nuclear tracking regime . . . with the objective of promptly detecting primary containment failure or misdirection of material."[392] This statement appears puzzling since BNFL had previously made claims, with the full support of the European Atomic Energy Community (Euratom), proclaiming the existence of near-real-time accountancy (NRTA) at THORP. For example, in a paper delivered at an IAEA safeguards symposium in 2001, a joint BNFL-Euratom team stated that: "Near Real Time Materials Accountancy (NRTMA) is fully operational in THORP, providing regular assurance of high quality material control."[393] In retrospect, this claim appears to have been exaggerated, at the least.

At the time of the incident, the plant was under Euratom safeguards. This institution has identical timeliness criteria as the IAEA for uncovering diversions of nuclear material (e.g., the detection of one SQ of direct-use fissile material within 1 month). However, Euratom failed to detect the MUF despite having access to the operators' accountancy records, as well as supposedly having access to process data, upon which it performed its own statistical tests.[394] Neither the plant operators nor the Euratom inspectors suc-

390. BNFL, "Media Response: Publication of Materials Unac- counted For (MUF)," press release, February 17, 2005.
391. BNFL, Board of Inquiry Report, "Fractured Pipe With Loss of Primary Containment in the THORP Feed Clarification Cell," May 26, 2005, p. 5.
392. Ibid., p. 15.
393. Barry Jones et al., BNFL, and Claude Norman et al., Europe- an Commission, Euratom Safeguards Office, "NRTMA: Common Purpose, Complementary Approaches," IAEA-SM-367/8/03, IAEA Safeguards Symposium, October-November 2001, IAEA, Vienna, Austria.
394. Ibid., p. 5.

cessfully detected the leak or sounded an alarm for 8 months—many times longer than the timely warning requirement. This incident suggests that even state-of-the-art safeguards cannot come close to satisfying the IAEA's explicit standards for detecting missing fissile material before it could be fabricated into a weapon.

France.

Along similar lines to the BNFL incident, the now closed MOX fuel facility in Cadarache, France, which operated under Euratom safeguards, encountered MUF situations twice during the last decade. This facility was operated from 1961 to 2004 by Cogema and then by Areva, which acquired Cogema. In 2002, the Euratom Safeguards Agency reported that "the annual verification of the physical inventory at Cogema-Cadarache plant in France found an unacceptable amount of material unaccounted for (MUF) on the plutonium materials [SIC]."[395] The problem was later attributed to the differences between measurement techniques by inspectors and operators, and to poor definitions of materials in historical accounting records. (If the latter were the issue, it is unclear why the MUF problem would not have arisen until 2002.) In September 2004, it was reported that Euratom finally had responded to Cogema's explanation of the 2002 MUF finding.[396] Thus, it took at least 2 years to resolve the discrepancy. Despite this explanation, the problems at the facility persisted.

In October 2009, the French Nuclear Safety Authority ordered the halt of decommissioning operations at the facility. When the facility had closed in 2004, its former operator, Areva, estimated that there would be a MUF of approximately 8-kg of plutonium due to holdup in the plant's gloveboxes—which are shielded hot cells along the process line in which technicians can remotely manipulate the nuclear material. However, 2 weeks into the cleanup of the facility, the French Atomic Energy Commission announced that it had already collected 22-kg and projected that the total might rise to 39-kg of MUF.[397] While the plutonium holdup might have accumulated in the gloveboxes over a long period of time, Areva's underestimation of the amount by almost five SQs suggests that the plant's accounting system failed and that the Euratom safeguards were insufficient to detect the potential diversion of several bombs' worth of fissile material. The repeated failure of safeguards in nuclear-weapons states to meet the IAEA detection standards, despite employing some of the most advanced accounting technologies in the world, raises serious questions about whether IAEA safeguards can achieve their objectives.

Japan.

Japan has boasted that it cooperates fully with the IAEA and applies the world's most advanced safeguards. Despite that, three of its fuel-cycle facilities have suffered substantial accountancy failures. This record raises serious concerns about the ability of safe- guards to detect the diversion of fissile materials in a timely manner in any country.

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395. European Commission, "Report from the Commission to the European Parliament and Council: Operation of Euratom Safeguards in 2002," p. 9.
396. Ann MacLachlan, "With Eurofab imminent, MUF issue said cleared up for Cadarache plant," *Nuclear Fuels*, Vol. 29, No. 20, September 27, 2004, p. 12.
397. Ann MacLachlan, "CEA, Areva Criticized for Handling of Plutonium at Closed ATPu Plant," *Nuclear Fuels*, Vol. 34, No. 21, 2009.

At the Plutonium Fuel Production Facility (PFPF), a MOX fuel plant at Tokai-mura, the problem of residual holdup led to a significant material accountancy failure. Soon after the plant started up in 1988, operators noticed the problem of plutonium becoming stuck in gloveboxes. In response, the plant operator, Japan's Power Reactor and Nuclear Fuel Development Corporation (PNC), in conjunction with safeguards experts at the U.S. Los Alamos National Laboratory, designed a nondestructive assay (NDA) method to measure residual holdup *in situ*—that is, without dismantling the hot cells—known as the Glovebox Assay System (GBAS). However, the system's imprecision contributed to an overall measurement uncertainty of about 15 percent.

By 1994, the plant's MUF had grown to about 69-kg of plutonium. Because of the measurement uncertainty associated with the GBAS, even if the entire MUF were residual holdup, the IAEA could not exclude the possibility—with a confidence level of 95 percent, based on NDA measurements alone—that at least one SQ had been diverted. Consequently, the IAEA wanted PNC to cut open the plant's gloveboxes, remove the holdup directly, and measure it with destructive assay methods. PNC balked at this request, and the dispute remained unresolved until the Nuclear Control Institute—a Washington-based, nonproliferation advocacy group—publicly disclosed the existence of the discrepancy in 1994. After that disclosure, PNC agreed to shut down the plant, recover the holdup, install new equipment to reduce further holdup accumulation, and implement improved NDA systems to measure more accurately any future residual holdup. After an expenditure of $100 million to remove and clean out old gloveboxes and install new ones, PNC announced in November 1996 that it had reduced the MUF to less than 10-kg (but not less than one SQ). This partial resolution of the MUF issue took more than 2 years from the time the situation became public, which contrasts starkly with the IAEA's timely warning standard of 1 month for such fissile material that can be used directly to make a nuclear weapon.

Another long-unresolved MUF issue at Tokai was associated with the accumulation of plutonium-laden fuel scrap resulting from decades of MOX research and production activities at the site.[398] Press reports in the mid-1990s indicated that the scrap inventory at Tokai contained between 100 and 150-kg of pluto- nium.[399] However, much of this scrap was in an impure form that could not be accurately measured via NDA methods. An NDA instrument known as the Plutonium Scrap Multiplicity Counter (PSMC), developed by Los Alamos, was relatively effective for measuring pure scrap plutonium but much less so if the material was contaminated with moisture or light elements that could generate neutrons through (α,n) reactions. For heavily contaminated scrap, the measurement imprecision ranged from 10 to 50 percent, well above the 4 percent uncertainty cited by the IAEA as the international standard for scrap measurements.[400] Even with the PSMC's best case of 10-percent average imprecision, the uncertainty associated with measuring a scrap inventory containing 150-kg of plutonium would be greater than one SQ. Indeed, more than six SQs would have to be diverted to yield a 95 percent chance of detecting a diversion. Accordingly, the IAEA wanted the plant operator, PNC, to chemically purify the scrap and then use destructive assay to measure the plutonium more precisely. In 1998, the IAEA announced a formal agreement under which PNC would embark on a 5-year program "aimed at reducing the inventory of heterogeneous scrap material," which would be "gradually homogenized to allow enhanced verification, including destructive analysis."[401] No

398. Edwin S. Lyman, "Japan's Plutonium Fuel Production Facility: A Case Study of the Challenges of Nuclear Material Accountancy," 39th Annual Meeting of the Institute of Nuclear Ma- terials Management (INMM), Naples, FL, July 1998.
399. Mark Hibbs, "PFPF Holdup Pu Inventory Under 10 kg; R&D Work to Focus on Monju Fuel," *Nuclear Fuel,* November 4, 1996, p. 15.
400. *IAEA Safeguards Glossary,* 2001 Ed., Vienna, Austria: IAEA, Table III, p. 53, available from www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/NVS3_prn.pdf.
401. *IAEA 1998 Annual Report*, p. 65.

further information appears to be available on the status of this program, except for a brief mention in the IAEA 2000 Safeguards Statement of a containment and surveillance approach for the receipt and storage of MOX scrap at the "Solution Critical Facility" in Japan.[402]

The older reprocessing plant at Tokai also has suffered substantial material accountancy failures due to measurement and estimation errors, since it began operating in 1977. In January 2003, Japan admitted that the cumulative shipper-receiver difference—that is, the amount of plutonium that was estimated to have been shipped to the reprocessing plant in spent fuel minus the amount of separated plutonium that had actually been measured—was 206-kg, or about 25 SQs. This was nearly 3 percent of the total plutonium estimated to have been processed in the plant over its lifetime. A few months later, Japan revised its figures, claiming that the actual discrepancy was only 59-kg, because the remainder was either bound in the hulls of the spent fuel's cladding (12-kg), had been discarded with high-level liquid waste (106-kg), or had decayed into americium-241 (29-kg). However, it was unclear how figures as precise as these were derived, given the uncertainties inherent in measuring the plutonium in cladding hulls and in high-level waste, and in assessing the isotopic content of the spent fuel prior to reprocessing.

Japan's newest fuel-cycle facility is the larger, Rokkasho-mura Reprocessing Plant, which is now scheduled to commence commercial operations in 2023. Starting in the 1990s during design and construction, there was a massive multinational effort to develop and implement a state-of-the-art safeguards system at Rokkasho. Unfortunately, issues of cost and convenience played a major role in development of the safeguards approach and resulted in many questionable compromises. For instance, instead of having its own, independent, on-site analytical laboratory, the IAEA must share a laboratory with the facility operator, which raises the potential for tampering.

The IAEA itself admits that, after 15 years of designing the safeguards approach, the detection goals still cannot be met at the facility. In 2006, Shirley Johnson, the former head of the Rokkasho safeguards project in the IAEA's Department of Safeguards, acknowledged that even if the overall measurement uncertainty were between 0.7 and 0.8 percent at Rokkasho, the system could not come close to the detection goal of one SQ.[403] In a 2009 report for the International Panel on Fissile Materials (IPFM), Johnson reiterated the continuing problems in reducing measurement uncertainty, and called for complementary measures to address the concern:

> "For a large facility like the Rokkasho Reprocessing Plant, which has an annual throughput of 800 tons of spent fuel containing about 1 percent plutonium (about 8,000-kg), a 1-percent uncertainty translates into an overall measurement uncertainty of 80 kilograms plutonium—10 significant quantities. For this reason, the IAEA requires added assurance by additional measures. Many of these could be carried out during short-notice random inspections."[404]

Unfortunately, such complementary measures have not yet been implemented. Nor have NRTA technologies solved the problem. Recent results from the performance of NDA solution monitoring systems at Rokkasho indicate that they also have high measurement uncertainty. For instance, it was reported that

402. *IAEA 2000 Annual Report,* p. 102, available from www.iaea. org/Publications/Reports/Anrep2000/safeguards.pdf.
403. Shirley Johnson, IAEA, personal communication, July 27, 2006.
404. Shirley Johnson et al., "Meeting the Safeguards Challenges of a Commercial Reprocessing Plant," 7th International Conference on Facility Operator-Safeguards Interface," Charleston, SC, February 29-March 4, 2004, p. 10.

the Plutonium Inventory and Management System (PIMS), which is designed to perform assays on relatively pure plutonium and uranium mixtures, has a total measurement uncertainty of 6 percent (+/-).[405]

Although Japan sometimes blocks intrusive measures, claiming proprietary concerns, the IAEA has never accused the country of doing so out of an intention to divert fissile material. Indeed, it is despite Japan's apparent good-faith efforts to cooperate with the IAEA that its state-of-the-art safeguards have proved inadequate. As a result, the IAEA does not have high confidence that it could give timely warning of a potential diversion of enough fissile material for one or more nuclear weapons.

The shortcomings of safeguards are still greater in countries that withhold full cooperation from the IAEA and may have proliferation aspirations, such as Iran. As noted by the team that developed the safeguards approach for Rokkasho, "The most important factor leading to the success" of a safeguards system is "the open and full cooperation between all parties—the IAEA, the State, and the operator."[406] Thus, even potential future enhancements of safeguards would likely fall short if there were an uncooperative or adversarial relationship between these parties. This is a crucial consideration as the IAEA and the world consider the expansion of nuclear power and fuel-cycle facilities to states with uncertain commitments to nuclear nonproliferation.

Iran.

Since 2003, the IAEA and international community have become increasingly concerned that Iran may use its enrichment technologies to produce highly enriched uranium for a nuclear weapon. To date, Iran generally has enriched no higher than to 20 percent at its three declared enrichment facilities (except for one small batch that inexplicably was enriched to around 27 percent),[407] and mostly to only about 4 percent. Ostensibly, the 20-percent enrichment is for research-reactor fuel, and the 4-percent enrichment is for power reactor fuel, although none of this uranium has yet actually been used as fuel.

Several experts have analyzed how quickly Iran could achieve a "breakout" by enriching sufficient highly enriched uranium (HEU) for a nuclear weapon. In October 2012, the Institute for Science and International Security assessed "that Iran would require at least 2-4 months to produce one SQ of WGU [weapons-grade uranium] at the Natanz Fuel Enrichment Plant," the largest of its three such facilities, if it started from its then existing stocks of low-enriched uranium. The report added that "the quickest estimates are 2 to 2.3 months."[408] Similarly, a Nonproliferation Policy Education Center (NPEC) report, published a month earlier, examined the breakout potential if Iran used all three of its enrichment facilities and concluded that "The total time required is 73 days, which is about 10 weeks or a little less than 2 1/2 months."[409]

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405. Y. Noguchi, "Validation and Performance Test of Plutonium Inventory Measurement System (PIMS) at Rokkasho Reprocessing Plant (RRP)," Institute of Nuclear Materials Management 48th Annual Meeting, Tucson, AZ, July 8-12, 2007.
406. Johnson et al., "Meeting the Safeguards Challenges of a Commercial Reprocessing Plant."
407. "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," GOV/2012/23, Vienna, Austria: IAEA, May 25, 2012, p. 6.
408. William C. Witt, Christina Walrond, David Albright, and Houston Wood, "Iran's Evolving Breakout Potential," Washing- ton, DC: Institute for Science and International Security (ISIS), October 8, 2012, available from isis-online.org/uploads/isis-reports/ documents/Irans_Evolving_Breakout_Potential.pdf.
409. Greg S. Jones, "'Not a Game-Changer' But Is the West Playing a Game with Iran That It Has Already Lost?" Washington, DC: Nonproliferation Policy Education Center (NPEC), September 10, 2012, available from www.npolicy.org/article.php?aid=1193&rid=4.

At the moment, IAEA inspections should be able to detect such an attempted breakout at a declared Iranian facility because "currently, inspections occur on average about once every 2 weeks, and some of them are unannounced."[410] But if Iran expands the number of its centrifuges and attempts to implement next-generation centrifuges, the required time for a breakout would shrink substantially. For example, according to the NPEC report, if Iran expanded its number of centrifuges by 12 times—without any improvement in technology and starting only from its stock of 4 percent low enriched uranium (LEU) rather than its 20 percent enriched stock—"these enrichment facilities could produce enough HEU for a nuclear weapon in just 2 weeks."[411] At that point, the IAEA's current schedule of safeguards inspections could not guarantee timely warning against a diversion of sufficient HEU for a nuclear weapon, even if Iran used only its declared enrichment facilities. An additional danger is that Iran could pursue a breakout at a clandestine enrichment facility, which current IAEA safeguards might not detect. As the IAEA conceded in August 2012:

> "While the Agency continues to verify the non-diversion of declared nuclear material at the nuclear facilities and LOFs [locations outside facilities] declared by Iran under its Safeguards Agreement, as Iran is not providing the necessary cooperation, including by not implementing its Additional Protocol, the Agency is unable to provide credible assurance about the absence of undeclared nuclear material and activities in Iran, and therefore to conclude that all nuclear material in Iran is in peaceful activities."[412]

Suspected diversion from Iranian nuclear facilities is not merely hypothetical. The IAEA has reported accounting discrepancies at a separate Iranian nuclear facility, the Jabr Ibn Hayan Multipurpose Laboratories (JHL).[413] In 2011, the IAEA conducted a physical inventory verification at JHL "to verify, *inter alia,* nuclear material, in the form of natural uranium metal and process waste, related to conversion experiments carried out by Iran between 1995 and 2002."[414] This inspection revealed a discrepancy of 19.8-kg between the amounts of nuclear material declared by the operator and measured by the agency. Subsequently, in August 2012, after additional analysis and evaluation of clarifications provided by Iran, the agency reported that it had been able to reduce the discrepancy, and would continue to work with Iran to resolve the remainder.[415] As of the time this chapter was written in early 2013, however, the discrepancy had yet to be fully resolved, more than a year after it was originally discovered. This does not bode well, especially if Iran continues to expand its nuclear fuel-cycle facilities.

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410. David Albright, Christina Walrond, William Witt, and Houston Wood, "Comments on Wall Street Journal Editorial and Our Breakout Estimates," Washington, DC: ISIS, October 30, 2012, available from isis-online.org/isis-reports/detail/comments-on-wall- street-journal-editorial-and-our-breakout-estimates/.
411. Jones, "'Not a Game-Changer'."
412. "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," GOV/2012/37, Vienna, Austria: IAEA, August 30, 2012, p. 11.
413. "Nuclear Iran: Jabr Ibn Hayan Multipurpose Laboratories," Washington, DC: ISIS.
414. "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council resolutions in the Islamic Republic of Iran," GOV 2012/9, Vienna, Austria: IAEA, February 24, 2012, available from www.iaea.org/Publications/Documents/ Board/2012/gov2012-9.pdf.
415. "Implementation of the NPT Safeguards Agreement," August 30, 2012.

Two Risks: Diversion and Theft

Civilian nuclear fuel-cycle facilities present two risks of clandestine removal of fissile material: diversion by states or theft by sub-state insiders for criminal or terrorist purposes. In both cases, the adequacy of safeguards is critical to providing the international community with timely warning to prevent the re- moved material from being fabricated into one or more nuclear weapons. The fundamental goal of IAEA safeguards is to establish an accounting regime capable of reliably providing timely warning of the suspected clandestine removal of as little as one bomb's worth of fissile material, thereby helping to deter and prevent such an outcome. (This chapter does not cover the risks of overt attacks by sub-state actors on fuel-cycle facilities or shipments, or overt proliferation by states at formerly civilian facilities, which must be addressed by other national and international countermeasures.) The potential for diversion and/or theft of bombusable nuclear material is present at three types of fuel-cycle facilities: (1) uranium enrichment, (2) reprocessing, and (3) MOX fuel fabrication. As explained later, these plants pose different vulnerabilities because of the different forms of fissile material that they routinely process.

Civilian enrichment facilities typically use centrifuges or other technologies to increase the percentage of the fissile U-235 isotope in uranium from its natural level of 0.7 percent to typically about 4 percent for use in the fuel elements of nuclear power plants. This output is known as "low enriched uranium," meaning less than 20 percent U-235, which is considered unsuitable for weapons. Civilian facilities typically do not produce "highly enriched uranium" (HEU)— meaning 20 percent or more U-235—which is considered necessary for weapons. Thus, the primary proliferation risks at civilian enrichment facilities are that the state could either (1) clandestinely produce and remove HEU, or (2) divert LEU to another facility not under safeguards for further enrichment.

Reprocessing facilities take the irradiated "spent" fuel that is removed from nuclear power plants and extract its plutonium (and uranium) for potential incorporation into fresh MOX fuel to be irradiated in nuclear power plants. The separated plutonium poses a major security risk because it can be fabricated directly into a nuclear weapon. Typically, such facilities contain plutonium in the form of oxides and other chemical mixtures that can either be used directly to make less efficient weapons or converted to metal for improved efficiency.

MOX fuel fabrication facilities take the plutonium oxide from reprocessing plants and mix it with uranium oxide to fabricate mixed-oxide fuel for nuclear power plants. MOX plants pose several security risks. Most obviously, they contain large amounts of separated plutonium oxide that can be used to make nuclear weapons. But even after the plutonium is combined with uranium to make bulk mixed-oxide material, and subsequently fabricated into MOX fuel, significant risk continues because the plutonium oxide can be separated out via chemical processes that are relatively straightforward. (This is much easier than reprocessing because the fuel is fresh and thus not highly radioactive.)

Scope of the Facilities

The countries of main focus are those that have signed the Nuclear Nonproliferation Treaty (NPT) as non-nuclear weapon states, whose fuel-cycle facilities are subject to IAEA safeguards. But the chapter also discusses such facilities in nuclear-weapon states and in states that have not signed the NPT, as these plants may also offer some important lessons, especially if they are under stringent commercial safeguard regimes comparable to those of the IAEA.

Approximately 25 nuclear fuel-cycle facilities are operating in the world, with others proposed or tem- porarily closed, as detailed later. In 2012, there were 18 civilian enrichment plants operating, and three more were planned in 11 countries. Table 6-1 indicates their location, name, operational status, opening year, safeguards status, and capacity. Five commercial reprocessing facilities were operating, one was temporarily closed, and one was preparing to start up (see Table 6-2).

Table 6-1: Civilian Enrichment Facilities.

Country	Facility Name	Operational Status	Opening Year	Safeguards	Capacity [tSWU/yr]
Argentina	Pilcaniyeu	Operating	2010*	Yes	20 – 3,000
Brazil	Resende	Operating	2005	Yes	115-120
China	Shaanxi	Operating	1997	Yes	1,000
	Lanzhou II	Operating	2005	Offered	500
	Lanzhou (new)	Operating	2005	Yes	500
France	Georges Besse II	Operating	2011	Yes	7,500–11,000
Germany	Gronau	Operating	1985	Yes	2,200–4,500
Iran	Natanz	Operating	2004	Yes	120
	Qom	Operating	2012	Yes	5
Japan	Rokkasho	Operating	1992	Yes	1,500
Netherlands	Alemo	Operating	1973	Yes	5,000 – 6,000
Russia	Angarsk	Operating	1954	Offered	2,200–5,000
	Novouralsk	Operating	1945	No	13,300
	Zelenogorsk	Operating	2009	No	7,900
	Seversk	Operating	1950	No	3,800
United Kingdom	Capenhurst	Operating	1972	Yes	5,000
United States	Paducah, KY	Shutdown proposed	1954	Offered	11,300
	Piketon, Ohio	Planned	2013?	Offered	3,800
	Eunice, NM	Operating	2010	Offered	5,900
	Areva Eagle Rock, Idaho	Planned	Postponed	Offered	3,300–6,600
	Global Laser Enrichment, Wilmington, NC	Planned	2013	?	3,500–6,000

Sources: Nuclear Fuel Cycle Information System, Vienna, Austria: IAEA, available from infcis.iaea.org/NFCIS/NFCISMain.asp? Order=1&RPage=1&Page=1&RightP=List; and Global Fissile Materials Report 2011, Princeton, NJ: International Panel on Fissile Materials, p. 32.

Table 6-2: Civilian Reprocessing Plants.

Country	Facility Name	Operational Status	Opening	Safeguards	Capacity (tHM/yr)
China	Lanzhou Pilot Plant	Operating	2001	No	50–100
France	Areva La Hague UP2	Operating	1996	Yes	1,000
	Areva La Hague UP3	Operating	1990	Yes	1,000
Japan	Rokkasho	Starting Up	2007	Yes	800
	Tokai	Temporarily Shut Down	1977	Yes	200
United Kingdom	B205	To be closed after cleanup	1964	Yes	1,500
	THORP	Operating	1994	Yes	1,200

Sources: Nuclear Fuel Cycle Information System, Vienna, Austria: IAEA, available from infcis.iaea.org/NFCIS/NFCISMain.asp? Order=1&RPage=1&Page=1&RightP=List; and Global Fissile Materials Report 2011, Princeton, NJ: International Panel on Fissile Materials, p. 33.

As for MOX fabrication facilities, in the wake of the UK's 2011 announcement that its plant would close, only three commercial facilities—one each in France, Japan, and Russia—are currently in operation. Three more are planned to open during the next 4 years in Japan, Russia, and the United States (see Table 6-3). Japan Nuclear Fuel Ltd. had originally planned to open the Rokkasho-mura MOX plant in 2015, but the 2011 Fukushima nuclear disaster delayed construction on the facility by a year.[416] In Russia, the Mining & Chemical Combine plans to open a MOX facility at Zheleznogorsk in 2014. The U.S. MOX fuel facility at Savannah River will use plutonium from disassembled nuclear warheads and is scheduled to start operations in 2016 and begin producing commercial fuel in 2018.[417]

416. "MOX Plant Construction Shown," *The Japan Times*, November 2, 2012, available from www.japantimes.co.jp/text/nn20121102b2.html.

417. Rob Pavey, "MOX Facility at SRS Gets Powdered Plutonium Feedstock," The Augusta Chronicle, November 16, 2012.

Table 6-3: Civilian MOX Fuel Facilities.

Country	Facility Name	Operational Status	Opening	Safeguards	Capacity (tHM/yr)
France	MELOX-Marcoule	Operating	1995	Yes (Euratom)	195
Japan	Tokai	Operating	2007	Yes	10
	Rokkasho	Planned	2016	Yes	130
Russia	Mayak - Paket	Operating	1980	No	5
	Zheleznogorsk	Planned	2014		60
United States	Savannah River	Planned	2018		100

Sources: Nuclear Fuel Cycle Information System, Vienna, Austria: IAEA, available from infcis.iaea.org/NFCIS/NFCISMain.asp?Order= 1&RPage=1&Page=1&RightP=List; and "Mixed Oxide Fuel," London, UK: World Nuclear Association, available from www.worldnuclear.org/info/inf29.html.

Technical and Political Challenges

The nonproliferation community has been aware for decades of the technical and political challenges facing safeguards. In 1990, Dr. Marvin Miller of the Massachusetts Institute of Technology (MIT) published a seminal paper, "Are IAEA Safeguards on Bulk-Handling Facilities Effective?" highlighting these challenges. Despite some progress over the past 2 decades, many of the challenges that Dr. Miller highlighted in 1990 still persist.

IAEA safeguards for nuclear facilities were designed with the objective of detecting with timely warning the diversion of a significant quantity of fissile material. An SQ is the "approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded."[418] In other words, an SQ is the estimated minimum amount of uranium or plutonium (or other exotic fissile material) that a state or nonstate actor would need to build a nuclear weapon.

Depending on the type and form of fissile material, the IAEA guidelines adjust the amount that qualifies as an SQ and the deadline for timely warning. For unirradiated, direct-use nuclear material, an SQ is defined as 8-kg of plutonium, or 25-kg of U-235 in HEU, and timely warning is defined as 1 month after an abrupt diversion (or 1 year after the start of a gradual diversion). In 1975, the Standing Advisory Group on Safeguards Implementation (SAGSI) was established as a group of external experts appointed by the IAEA Director General to provide feedback on safeguards standards, among other functions.

Material accountancy is how the IAEA aims to detect the diversion of nuclear material at civilian fuel-cycle facilities. This is analogous to an audit. Operators of nuclear facilities prepare a material balance for a specific period of time showing that all nuclear material can be accounted for. To prepare this balance, the operators add material inputs—and subtract removals—from the quantity indicated at the start of the accounting period, yielding an amount that should match the ending physical inventory. The IAEA per-

418. *IAEA Safeguards Glossary,* p. 23.

forms an independent assessment on at least some of the data provided by the facility operator to verify that there has not been any deliberate falsification of data.[419]

Discrepancies between the operator's final physical inventory and the amount that its records indicate should be present are labeled MUF. Such discrepancies can arise from problems such as accumulation of residual holdup in the process lines, accumulation of scrap and waste materials in other material forms that are hard to assay, inaccuracies in nuclear material estimation methods, operator incompetence, diversion, or theft. MUF is often caused by residual holdup, resulting from the adhesion of fissile-material powders on process equipment, including in cracks, corners, and pores. Because of the layout and design of fuel-cycle facilities, these MUFs can grow over time and may only be resolved by dismantlement and careful cleanout. Unless and until the source of the MUF can be identified, it is impossible to rule out the possibility of diversion or theft, which poses a dilemma. If inspectors declare a possible theft or diversion, it may well be a false alarm. But if they refrain from doing so for fear of a false alarm, it may be impossible to satisfy the IAEA's timely warning criteria.

False alarms thus pose a serious quandary for safeguards. The SAGSI guidelines recommend that safeguards be stringent enough to provide at least a 90 to 95 percent probability of detecting a diversion with a false alarm rate of less than 5 percent. Some critics have argued that this detection probability is too low, because it permits a 5 to 10 percent chance of a diversion going unnoticed. But merely raising the probability of detection, if all else remains equal, will also increase the false-alarm rate. Such increases in false alarms are a nuisance and impose costs by interrupting facility operations. Moreover, based on past experience, high false-alarm rates may spur operators to ignore alarms or even switch off the detection systems, thereby perversely reducing the probability of detection.

Unfortunately, real-world detection probabilities at fuel-cycle facilities are even lower than recommended by SAGSI. The IAEA has acknowledged that it cannot meet the goal of a 90 to 95 percent probability of detecting the diversion of an SQ. So, instead, the IAEA adopted a relaxed standard known as the "accountancy verification goal" (AVG), which was "based on a realistic assessment of what then-current measurement techniques could actually detect," according to a U.S. congressional report.[420] In other words, rather than designing safeguards to meet the desired detection standard, the IAEA instead has lowered that detection standard, so it could be satisfied by current safeguards.

The AVG is based on a measure called E, defined as the "minimum loss of nuclear material which can be expected to be detected by material accountancy," which varies depending on a facility's input, among other factors. The formula for E was derived from the joint requirements of a 95 percent confidence of detecting a diversion and a 5 percent false-alarm rate. For a large reprocessing facility, based on an input uncertainty of 1 percent (+/-) and an annual input of 800 metric tons of heavy metal (spent fuel), the value for E would be 246-kg of plutonium, or more than 30 SQs. In other words, there would be less than a 95 percent probability of detecting a diversion of 30 bombs' worth of plutonium. Any smaller diversion would have an even lower probability of detection. In particular, the probability of detecting the diversion of a single SQ—enough for a nuclear weapon—would be minimal.

Despite technological advances in monitoring and accounting systems since 1990, large MUFs have occurred repeatedly at facilities with IAEA-quality safeguards, as detailed earlier. These failures have arisen

419. Ibid., p. 277.

420. U.S. Congress, Office of Technology Assessment, Nuclear Safeguards and the International Atomic Energy Agency, OT ISS-615, Washington, DC: U.S. Government Printing Office, June 1995, p. 73.

both in non-nuclear weapons states, subject to IAEA safeguards, and in nuclear weapons states subject to analogous domestic regulations.

Proposed Improvements

For at least 3 decades, nonproliferation experts have outlined theoretical proposals for improving safeguards. But practical obstacles, including proprietary concerns, have prevented their thorough implementation. In his 1990 paper, Miller focused on three areas:

1. **Reducing measurement uncertainty in the chemical process area**. Unfortunately, no progress is apparent in this realm. As of 2001, the IAEA's "expected measurement uncertainty" associated with closing a material balance at a reprocessing plant remains at 1 percent.[421] Miller reported the same value in 1990.

2. **Near-real-time accountancy on a weekly basis to improve the detection of protracted, low-level diversion**. In NRTA, inventories are taken and material balances closed on a much more frequent basis than the conventional annual physical inventory. For instance, Miller showed that the threshold for detection of an abrupt diversion of one SQ of plutonium at a fuel-cycle facility could be accomplished by use of NRTA with physical inventories conducted on a weekly basis. However, given that the time to take a physical inventory of a large facility is approximately 1 week—including preparation time, cleanout of process of equipment, measurement of the inventory, and reconciliation of the anomalies—such a high frequency of physical inventories is impractical.[422] Therefore, NRTA must resort to nondestructive assay measurements of in-process materials where possible, and its effectiveness will depend in large part on the uncertainties associated with these measurements. A major question is whether NDA techniques have improved over the past 22 years to the extent that the benefits of NRTA can be fully realized.

3. **Reducing measurement error of plutonium in the waste stream, such as in cladding hulls and sludges.** Over the past decade, Los Alamos National Laboratory and other labs have explored ways to improve the capabilities of NDA instruments for waste measurements. The development of neutron multiplicity counters and high-efficiency epithermal neutron counters showed some promise in improving the precision of measuring plutonium in waste drums. However, these instruments do not perform well when measuring low-assay, contaminated, and heterogonous plutonium materials—as is typical in waste streams.

A holistic approach to reducing measurement uncertainties is known as safeguards by design (SBD). Under SBD, future civilian nuclear fuel-cycle facilities would be designed, constructed, and operated in a manner to incorporate the most advanced technology and systems to enforce IAEA safeguards. Proponents of SBD assert that this approach can:

421. *IAEA Safeguards Glossary*, p. 53.

422. Thomas G. Clark et al., Westinghouse Savannah River Company, "Continuous Material Balance Reconciliation for a Modern Plutonium Processing Facility," 45th Annual Meeting of the Institute of Nuclear Materials Management (INMM), July 18- 22, 2004, Orlando, FL.

> "... ensure the timely, efficient, and cost effective integration of international safeguards and other nonproliferation barriers with national material control and accountability, physical protection, and safety objectives into the overall design process for a nuclear facility."[423]

But the future viability and success of SBD depends upon developing better monitoring and accountancy equipment, reducing the costs associated with these new designs and technologies, and alleviating proprietary concerns.

While such technical solutions could in theory enhance IAEA safeguards, proprietary and sovereignty concerns have hindered their implementation. States and nuclear firms have been reluctant to allow the IAEA access to the design, construction, and operation of their fuel-cycle facilities because they fear loss of intellectual property. For example, in 2004, Brazil initially prevented IAEA officials from inspecting equipment at the Resende enrichment facility, in order to protect proprietary information. When the IAEA inspectors arrived at the plant, they discovered that large portions of it were behind walls and coverings.[424] Later in 2004, Brazil and the IAEA did reach an agreement to allow the inspectors to visit the site.[425] However, this incident demonstrates that even countries that have abandoned their pursuit of nuclear weapons and are responsible, active members of the international community (such as Brazil) are reluctant to provide the IAEA with unrestricted access to commercial fuel-cycle facilities due to proprietary concerns.

Other countries, such as Iran, may be hesitant to comply with the IAEA so that they can maintain their weapons option. Such countries may fear that the IAEA would provide detailed information about their facilities to their enemies. Top Iranian officials express this fear. For example, then-Iranian President Mahmoud Ahmadinejad labeled the head of the IAEA a puppet of the United States, and he accused the IAEA of making "illegal requests" during its inspection efforts.[426] In September 2012, the head of Iran's Atomic Energy Organization, Feyerdoon Abbasi-Davan, claimed that "terrorists and saboteurs might have intruded the agency and might be making decisions covertly."[427] Despite nominally placing all of its nuclear facilities under a safeguards agreement, Iran continues to deny the IAEA unfettered access to all of its nuclear-related facilities.

Given the limitations of safeguards, the IAEA increasingly has relied during the last 2 decades on complementary measures of containment and surveillance (C/S), especially seals and cameras. For example, reprocessing plants have begun to utilize seals on their tanks containing liquid plutonium nitrate, which is an interim form of the material during the plant's operation, in order to detect unauthorized withdrawals. Some reprocessing plants also have installed cameras to monitor the spent fuel pool and the transfer of spent fuel to the chop-leach cell to detect efforts to divert for clandestine reprocessing. Unfortunately, many parts of a reprocessing plant cannot be monitored with cameras or seals, because of the myriad

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423. T. Bjornard et al., "Improving the Safeguardability of Nu- clear Facilities," presented at Institute of Nuclear Materials Management 50th Annual Meeting, July 2009, available from www.inl. gov/technicalpublications/Documents/4310590.pdf.
424. "Sources: Brazil blocks nuclear inspectors," *CNN*, April 4, 2004, available from www.cnn.com/2004/WORLD/americas/04/04/ brazil.nuclear/index.html.
425. "Diplomats: IAEA, Brazil Reach Agreement," *USA Today*, October 6, 2004.
426. "Iran Does Not Need Nuclear Weapons, Says Ahmadinejad," *BBC*, November 8, 2011, available from www.bbc.co.uk/news/ world-middle-east-15637539. "Ahmadinejad: Iran 'Could Have Behaved Better', IAEA Has 'Double Standards'," Christian Science Monitor, September 25, 2012, available from www.csmonitor.com/ World/Middle-East/2012/0925/Ahmadinejad-Iran-could-have-behaved- better-IAEA-has-double-standards.
427. "Iran Warns of IAEA 'Terrorist Infiltration'," *BBC*, September 17, 2012, available from www.bbc.co.uk/news/world-middle- east-19627623.

pipes, valves, pumps, and tanks. Thus, although C/S measures are a useful complement to safeguards, they are no substitute for better accounting measures, such as NRTA.[428]

In 1997, due to concern about clandestine facilities, the IAEA introduced an additional protocol, which it aimed to negotiate with each state already subject to a comprehensive safeguards agreement. This would provide the IAEA "complementary access . . . to assure the absence of undeclared nuclear material and activities."[429] To induce states to sign the additional protocol and to save money, the IAEA also introduced the concept of integrated safeguards. Under this approach, the agency relaxes the inspection requirements at declared facilities, on grounds that its "state level" approach can detect any nondeclared facilities where diverted material would need to be further processed for a nuclear weapon. The state-level approach depends on factors such as the state's own domestic accounting mechanisms and its willingness to accept remote monitoring and short-notice random inspections.[430] As the agency explains:

> "... when the IAEA has drawn a conclusion of the absence of undeclared nuclear material and activities in that State . . . [accountancy] measures may be applied at reduced levels at certain facilities, compared with the measures that would have been applied without this conclusion."[431]

SAGSI concluded in 2004 that such "Safeguards Criteria were basically sound,"[432] and in 2010, the IAEA reported that 47 states had implemented integrated safeguards.[433]

But serious questions have been raised about whether integrated safeguards are an adequate substitute for facility-level accounting. The approach depends on high confidence that the IAEA can detect all clandestine facilities in a country and that fissile material cannot be diverted to a second country for processing, both of which are questionable assumptions.[434] Some aspects of the state-level approach are laudable, including less predictable inspections and aiming to discover clandestine facilities,[435] but these should not come at the expense of watering down facility-level safeguards. Otherwise, integrated safeguards could wind up weakening, rather than strengthening, protections against misuse of fissile material.

Some nuclear security advocates, such as the IPFM, have proposed new ways to monitor fuel-cycle facilities in nuclear-weapons states—as would be required under a proposed Fissile Material Cut-Off Treaty (FMCT)—which might also be applicable at some facilities subject to IAEA safeguards.[436] To reduce costs of monitoring under an FMCT, an IPFM report in 2009 suggested that IAEA timeliness requirements could be relaxed in return for new verification and monitoring tools and methods, which it said would result in "only a relatively moderate increase in measurement uncertainties."[437] For example, at operating

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428. Marvin Miller, "Are IAEA Safeguards on Plutonium Bulk- Handling Facilities Effective," Paul L. Leventhal et al., eds., *Nuclear Power and the Spread of Nuclear Weapons*, Washington, DC: Brassey's, 2002, pp. 283-284.
429. Mark Hibbs, "The Unspectacular Future of the IAEA Additional Protocol," Washington, DC: Carnegie Endowment, April 26, 2012, available from carnegieendowment.org/2012/04/26/unspectacular-future-of-iaea-additional-protocol.
430. *IAEA Safeguards: Staying Ahead of the Game*, Vienna, Austria: IAEA, July 2007, available from www.iaea.org/Publications/ Booklets/Safeguards3/safeguards0707.pdf.
431. *IAEA Safeguards Glossary*, p. 28.
432. "IAEA, Safeguards Statement for 2004," para. 52, p. 11.
433. "IAEA, Safeguards Statement for 2010."
434. Ed Lyman, "Role of nuclear material accounting and control in the NPT," IEER Conference, Nuclear Dangers and the State of Security Treaties, United Nations, New York, April 9, 2002.
435. Herman Nackaerts, "The Future of Safeguards: Adapting to Change," January 17, 2012.
436. Shirley Johnson, *The Safeguards at Reprocessing Plants under a Fissile Material (Cutoff) Treaty*, Princeton, NJ: International Panel on Fissile Materials, February 2009, available from fissilematerials.org/library/rr06.pdf.
437. Ibid., p. 8.

commercial facilities, the report recommended short-notice random inspections rather than continuous inspector presence.[438]

While IAEA safeguards are an international audit mechanism, analogous domestic measures are generally known as state systems of accounting and control (SSACs), which help monitor nuclear materials in a country and may provide the framework for the application of safeguards under an agreement between the state and the IAEA. These agreements include, but are not limited to, protocols for measurement systems to determine quantities of nuclear material and procedures governing the taking of a physical inventory. The IAEA does not have formal authority to address subnational threats, such as theft by workers at a facility ("insiders"). But improving SSAC to help the IAEA detect diversions by the state can also provide the operator an enhanced capability to detect diversions by sub-state insiders.[439] Unfortunately, additional aspects of domestic security that are important in countering internal threats, such as access authorization programs, remain out of the IAEA's formal domain, even under the provisions of the 2005 amendment to the Convention on Physical Protection of Nuclear Material which, in any case, has not yet entered into force. This distinction between state and nonstate actors is artificial when their interests are intertwined, so it may hinder efforts to build comprehensive systems to effectively ensure that civil nuclear facilities do not become covert sources of fissile material for states or subnational groups.

Domestic authorities also are responsible for "physical protection," which seeks to detect and prevent loss of nuclear material in real time, in contrast to accountancy that can only detect it after the fact. Many of the technological aspects of physical protection are known as material control and accounting (MC&A), which comprises aspects of safeguards, in addition to containment and surveillance. At fuel-cycle facilities, MC&A includes but is not limited to locks, fences, walls, gates, and badging systems. It also may incorporate interior and exterior sensors such as video cameras and motion detectors to prevent outsiders from breaking in or insiders from gaining access to sensitive areas and materials, and to improve response time to alarms. Such systems also may monitor pedestrian and vehicle exits to detect attempts to remove materials.[440] Beyond MC&A—which comprises these technological approaches to detection, deterrence, and prevention of nuclear theft—physical protection programs also include additional response and deterrence elements, including armed forces.

Conclusion

Theoretical solutions to improve IAEA safeguards have been discussed for decades. However, proprietary, economic, and sovereignty concerns have limited the extent to which countries and private companies have implemented these theoretical solutions. Even in states that cooperate with the IAEA and apply sophisticated accounting mechanisms, such as Japan, safeguards at fuel-cycle facilities currently cannot come close to achieving their explicit goal of providing timely warning of a suspected diversion of one bomb's worth of fissile material. The prospects are even worse in states that resist cooperation and may wish to keep open their weapons option, such as Iran, and at facilities that employ first-generation safeguards.

438. Ibid., p. 10.
439. Miller, "Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?" p. 273.
440. Office of International Affairs, National Research Council, *Protecting Nuclear Weapons Material in Russia,* Washington, DC: National Academy Press, 1999, p. 53.

If the prospect of an undetected diversion or theft of fissile material is unacceptable to the international community, then it is imprudent to permit the construction of additional nuclear fuel-cycle facilities, or expansion of existing ones, especially in states of proliferation concern, unless and until safeguards can be substantially upgraded to meet the international community's explicit detection goals. Considerable resources should be devoted to research and development of such improvements. But if past experience is any indicator, significant progress is unlikely to occur anytime soon. That stubborn reality should inform nuclear policy decisions. Most importantly, it suggests that the international community should postpone consideration of expanding the recycling of spent nuclear fuel, because that would require additional reprocessing and MOX fuel fabrication facilities that cannot now be safeguarded adequately against diversion or theft for nuclear weapons.

Appendix B

Review: Why Marginal Improvements in Safeguarding Nuclear Fuel-Cycle Facilities Are Unlikely Ever to Be Enough

Ryan A. Snyder

In Appendix A, "Can the IAEA Safeguard Fuel-Cycle Facilities? The Historical Record," Alan Kuperman, David Sokolow, and Edwin Lyman provide a reminder of safeguarding challenges at fuel-cycle facilities by citing material accountancy failures at such facilities in England, France, Japan, and Iran. The known technical challenges of meeting the International Atomic Energy Agency (IAEA) safeguards objective are discussed, but many of the examples and much of the surrounding discussion reveal that limitations to safeguarding efforts are not merely technical. There are human factors that likely contributed to the material accountancy failures over months or years, as well as IAEA credibility considerations that probably delayed disclosures of material diversions. In addition, the technical challenge is greater than discussed, as nuclear weapons with sizeable yields can likely be manufactured with less material than was assumed.

Two examples of missing material that Kuperman, Sokolow, and Lyman cite are the 22 tons of uranium and 160 kilograms (kg) of plutonium found missing in 2005 at the Thermal Oxide Reprocessing Plant (THORP) in England, and the 206-kg of plutonium that was reported missing in 2003 at the Tokai reprocessing plant in Japan. It is tempting to claim that the IAEA simply lacks the capabilities to measure such diversions, but the amount of material missing in both cases suggests that either the measurement errors are much higher than claimed in the 2001 IAEA Safeguards Glossary or that no measurement or inexcusably few measurements were made until other signals alerted inspectors or operators to large amounts of missing material. It should be mentioned here that even though the IAEA was not responsible for safeguarding the THORP, there is no reason to assume that the technical capabilities of those responsible at the Euratom Safeguards Agency should have differed markedly from those at the IAEA.

The 206-kg found missing at Tokai was about 3 percent of the total plutonium processed over the plant's lifetime since 1977. The expected error for such a measurement at a reprocessing facility is about 1 percent, according to the IAEA.[441] While the percent of total throughput of the uranium and plutonium found missing at the THORP is not listed, the size of the leaks were almost certainly higher than 3 percent of total plant throughput between the roughly 8 months from the start of the leak to its discovery.

It is necessary here to mention what the IAEA says must be measured to have the required confidence that a material diversion has occurred. Any scientific measurement must have some uncertainty, so there is always some chance that a quantity is actually higher or lower than the number measured. This amount

441. *IAEA Safeguards Glossary*, 2001 Ed., Vienna, Austria: International Atomic Energy Agency (IAEA), p. 53, available from www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/NVS3_scr.pdf.

higher or lower divided by the measured value is called the measurement error, and the IAEA expresses this as a percentage. The IAEA also wants to be about 90-95 percent confident that, in fact, a measured material diversion has occurred, and this translates into needing measurements to differ from the original amount by 3.3 multiplied by the measurement error to claim this level of confidence. This rule is derived from basic statistics to reflect the IAEA's stated 90-95 percent confidence standard.

Knowing this, 3.3 times the expected error of 1 percent is 3.3 percent, which translates into an amount that is a bit higher than the 206-kg missing at Tokai when considering the total plant throughput. It is tempting to think that 206-kg of plutonium missing from a reprocessing facility could go undetected if it is only 3 percent of the total; it would not signal the 90-95 percent confidence needed for the IAEA to claim a diversion. However, if measurements with uncertainties of 1 percent were taken on multiple occasions over the life of the plant and if material equal to 3 percent of the throughput was indeed missing, statistics indicates that diversions over 3.3 percent of the throughput would still occasionally be measured and signal the necessary confidence to claim a diversion. The Tokai example suggests that either the measurement errors were not accurate to 1 percent or that measurements were not taken frequently enough to discover that material was missing.

Another way of thinking about such an idea is to consider counting out 100 pennies to make one dollar. If the measurement error here is 1 percent, it is expected that the total number of pennies counted would be between 99 and 101 most of the time. Now if a child entered the room and took three of the pennies without your knowledge, recounting them after the child's theft would most often give counts between 96 and 98. A count of 96 reflects a diversion equal to 4 percent of 100 and would exceed the minimum 3.3 percent difference needed to be confident that there has been a diversion. The important fact is that measurements with 1 percent error would sometimes create the appearance that four of the pennies are missing when only three have been stolen. This applies analogously to the missing 3 percent of plutonium from Tokai; frequent measurements would occasionally result in diversions appearing to exceed 3.3 percent. The statistics of 1 percent measurements demand such outcomes.

The accountancy failure at Tokai is explained by human errors and not measurement limitations. Either the IAEA does not know what the standard errors are in measuring equipment used around the world, or it is claiming greater precision than the instruments have; an additional possibility is that users of the equipment do not know how to use it. It is also possible that no or very few measurements were taken, which adds another element into safeguarding efforts. Perhaps inspectors with high confidence in the operators at a particular plant or inspectors safeguarding plants located in countries deemed unlikely to divert material for use in a nuclear weapon will be more likely to skip material accountancy measurements. When so much material is found missing in the examples Kuperman, Sokolow, and Lyman cite from Tokai and THORP, the questions raised go beyond the IAEA's technical capabilities.

Additional human factors need to be considered in discussions about the IAEA's credibility related to false alarms or claims of a diversion when, in fact, none has occurred. The IAEA aims to keep this below 5 percent, which statistical calculations show is the previously mentioned standard of at least 3.3 multiplied by the measurement error. This consideration can be understood in the following way: If 20 measurements are made that meet the IAEA's threshold for diversion, one of those measurements is statistically likely to be false.

It is important to be aware of the problems the IAEA might encounter upon falsely claiming that a diversion has occurred. The agency is only able to do its work if it receives cooperation from states and if it made a claim that turned out to be false, cooperation in implementing safeguards might disappear. A state could say the IAEA was pressured by the United States so it could claim it has nuclear weapons ambitions and is interested in rallying international opinion for economic sanctions or military action against it. Future collaborative efforts between states and the IAEA could be in jeopardy, and the loss in trust from such an event could be a major setback.

Even though the chance of false alarms is a quantitatively expressed measurement, the political factors in bringing a claim of material diversion are highly relevant and add a challenging layer to safeguarding efforts. Any measure of material diversion with the required confidence will likely be repeatedly examined before a claim is brought against a state; the understandable risks of being wrong would likely demand it. This process will take time and, in the real event that material has been diverted, provide a state with additional time to build a nuclear weapon. A state could also say that the IAEA is mistaken or that it needs to check its own records to resolve the accounting discrepancy. This could delay any punitive action and buy yet more time.

Such factors could also lead states to conclude that diversions into nuclear weapons should be attempted with well-prepared excuses in preparation for the IAEA raising alarms. A state might calculate that it could divert material only to wait and see if the IAEA detects it. If the IAEA sounds an alarm, a state could attempt to creatively smooth over the discrepancy and resolve it without fear of consequence. If the IAEA misses the diversion, then a state could proceed through the remaining clandestine steps to a bomb with greater confidence. That states considering the manufacturing of nuclear weapons will almost certainly give more thought into how to build them without detection than those trying to stop them raises the possibility that the IAEA is never likely to detect a material diversion it could confidently say was made for inclusion in a nuclear weapon. At least it seems unlikely, given the IAEA's constraints.

It is not unreasonable to ask whether the human factors in safeguarding efforts will always remain considerable limitations, no matter what improvements are made in measurement precision. The upgrades that Kuperman, Sokolow, and Lyman propose for safeguards would indeed be improvements, but they are all aimed at improving measurement error. Although vitally important, one must wonder whether any claimed improvements are indeed real and whether, if real, they would significantly improve efforts at meeting the IAEA's safeguards objective, which is:

> "... the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection."[442]

Might timely detection always be impossible when considering a state determined to build a nuclear weapon as quickly as possible upon diversion from a fuel-cycle facility? Improved measurement accuracy might provide greater confidence that, indeed, some material is missing, but what are the limitations of such improvements? How much increased confidence is possible as a result? Should the human factors already discussed weigh more heavily—or perhaps dominantly—in considerations of safeguarding limitations?

The one quantitative definition that Kuperman, Sokolow, and Lyman did not discuss in enough detail was the definition of a significant quantity (SQ). The IAEA defines a significant quantity as "the approximate

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442. The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons, IAEA Information Circular (INFCIRC) 153, Vienna, Austria: IAEA, June 1972, available from www.iaea.org/Publications/Documents/Infcircs/Others/ infcirc153.pdf.

amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded."[443] Kuperman, Sokolow, and Lyman use the IAEA's definition of 8-kg for a significant quantity of plutonium-239 (Pu-239), but this amount has been challenged as too large, given the information now publicly available about nuclear weapons design. This is an important oversight, as the effectiveness of a safeguards system depends on whether a diverted SQ can be detected, and the need to detect smaller quantities would place increased demands on safeguarding efforts. Most importantly, however, the IAEA's definitions in this regard are extraordinarily irresponsible if sizeable nuclear weapons can be built with smaller amounts of material than what the IAEA has defined as its concern. The question of whether it is possible to detect a diversion with the required confidence and raise a claim that the requisite material for a nuclear weapon is missing must meet a whole new standard. Such an error raises questions about how the IAEA views its role if it accepts the shortcomings of its own definitions.

The U.S. Department of Energy (DOE) has confirmed that 4-kg is sufficient for building a nuclear device in the case of Pu-239 and uranium-233 (U-233),[444] and others have suggested that only 1-kg can be used for these isotopes.[445] This shows that 8-kg should be considered too large. The relevant assumption here is that materials for neutron reflecting and compression techniques are accessible by non-nuclear weapons states for making sizeable bombs with less material.

Leaving aside the omission about significant quantities, Kuperman, Sokolow, and Lyman do lay out the technical challenges in safeguarding these facilities, challenges that guarantee many kinds of diversions by determined proliferators would go undetected. Nowhere, however, might the technical capabilities of the IAEA prove less relevant than in the case of Iran and the current state of its nuclear program. The danger Iran presents is the advancement of its program under IAEA safeguards, thereby shortening the time needed for acquiring the requisite material for a nuclear weapon. With recent hopes for diplomatic progress in curtailing the program notwithstanding, Iran's program reveals a limitation to safeguards no matter the current capabilities or prospective improvements in them. Although analysts differ slightly in how much time Iran might need to acquire the material for one bomb (usually assumed to be 20- to 25-kg of U-235), continued enrichment of uranium to 3.5 percent and acquisition of additional centrifuge capacity could very shortly, if it has not already, make the time needed for assembly of a nuclear weapon so short that detection of a material diversion for bomb assembly could not prevent one from being built. This judgment holds important implications for the future of nuclear proliferation, as states learn they are able to come so close under IAEA safeguards to a nuclear weapon that the world has no choice but to act as if they have one.

This raises the question of whether it will become increasingly futile to focus on improving the ability to detect a material diversion from a fuel-cycle facility. The lower political and economic costs of pursuing nuclear weapons under the guise of a safeguarded civilian nuclear power program, where a state can be assisted in the effort from international suppliers or may be increasingly able to build the needed fuel-cycle technologies indigenously, suggest that the United States needs to define what it considers unacceptable along the spectrum of nuclear capability with regard to the fuel cycle. To draw the line at proscribing an Iranian nuclear weapon—as the United States may argue—would prove unmanageable. Once the

443. *IAEA Safeguards Glossary*, p. 23.
444. Classification Bulletin WNP-86, Washington, DC: U.S. Department of Energy, February 8, 1994, states, "Hypothetically, a mass of 4 kilograms of Plutonium or Uranium-233 is sufficient for one nuclear device." (Although this sentence is unclassified, the full text of the bulletin is classified.) No such statement has been issued with respect to Uranium-235.
445. Thomas B. Cochran and Christopher E. Paine, *The Amount of Plutonium and Highly Enriched Uranium Needed for Pure Fission Nuclear Weapons*, Washington, DC: Natural Resources Defense Council, revised April 13, 1995.

requisite amount of material is produced, constructing and equipping a warhead is a relatively short and technologically straightforward process, almost certainly impossible to detect in a timely fashion. Not until a more effectual standard—and the credibility to enforce it—has emerged should improvement in the IAEA's abilities be regarded as helpful in preventing the manufacture of a bomb.

Kuperman, Sokolow, and Lyman have certainly provided a message that the nonproliferation community needs to hear more often, that the current technical capabilities of the IAEA make safeguarding fuel-cycle facilities very challenging. The bad news is that human factors and their interaction with these capabilities, as well as the inability of the United States to define what is unacceptable nuclear capability, make success in safeguarding less likely than even they suggest.

About the Authors

Thomas B. Cochran was a senior scientist at the Natural Resources Defense Council (NRDC) from 1973 until 2011, where he served as director of the Nuclear Program and held the Wade Greene Chair for Nuclear Policy. While at NRDC he initiated NRDC's Nuclear Weapons Databook Project. In the 1980s, he and Academician Evginiy P. Velikhov, vice-president of the Soviet Academy of Sciences, co-directed a series of NRDC-Soviet Academy of Sciences nuclear weapons verification projects, including the Nuclear Test Ban Verification Project, which helped to demonstrate the feasibility of utilizing seismic monitoring to verify a low-threshold test ban, and the Black Sea Experiment, which examined the utility of passive radiation detectors for verifying limits on sea-launched cruise missiles. He has served as a consultant to several government agencies and non-government organizations on energy, nuclear nonproliferation and nuclear reactor matters, including serving on the Secretary of Energy Advisory Board, the Department of Energy's Nuclear Energy Advisory Committee and several of its subcommittees. Dr. Cochran has also written extensive publications on nuclear energy and nuclear weapons issues. He received his Ph.D. in physics from Vanderbilt University in 1967. He is the recipient of the American Physical Society's Szilard Award and the Federation of American Scientists' Public Service Award, both in 1987. Dr. Cochran is a Fellow of the American Physical Society and the AAAS.

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Henry D. Sokolski is executive director of the Nonproliferation Policy Education Center and teaches graduate classes on nuclear policy at the University of Utah and the Institute of World Politics. He was recently appointed Senior Fellow for Nuclear Security Studies at the University of California at San Diego. Previously, he worked in the Pentagon as Deputy for Nonproliferation Policy, as a consultant to the National Intelligence Council, as a member of the Central Intelligence Agency's Senior Advisory Group, as a Senate military legislative aide to a member of the Senate Armed Services Committee, and as a special assistant on nuclear energy to the chairman of Senate's Tennessee Valley Authority oversight committee. He served on two congressional commissions on the prevention of WMD proliferation and has authored and edited numerous volumes on strategic weapons proliferation issues, including *Best of Intentions: America's Campaign against Strategic Weapons Proliferation.* Mr. Sokolski earned his graduate degree in political science from the University of Chicago.

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