Proceedings of the INMM & ESARDA Joint Virtual Annual Meeting
August 23-26 & August 30-September 1, 2021

POLICY IN REVIEW: PAST, PRESENT, AND PROSPECTS FOR SPENT NUCLEAR FUEL REPROCESSING

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ABSTRACT

The reprocessing of spent nuclear fuel (SNF) is a controversial step in the nuclear fuel cycle. Conventional PUREX or hydrometallurgical reprocessing can recover a large amount of usable material from spent fuel for recycling, thus removing plutonium, the most attractive weapons-usable material from SNF storage and disposal, which poses proliferation risks as it can be used for the manufacture of nuclear explosives. National policies have shifted away from reprocessing given this and other concerns, opting instead for "wait and see" or direct disposal options. Now, as a new generation of innovative power reactor designs emerges, some including recycling in their designs, reprocessing is re-entering the conversation about the future of nuclear power. Discussion is ongoing regarding the exact processes to be used to extract and recycle fuel, as well as the extent to which plutonium would be separated. Developers are moving forward with the design and licensing process, but their development may be brought to a halt if they pursue recycling in countries historically opposed to reprocessing. This paper surveys the history of reprocessing policies with a focus on the United States and Canada and uses historical trends to inform a discussion of the extent to which reactor developers might expect their recycling-based designs to push policies towards reprocessing. By doing so, this paper aims to further discussion about the prospects for fuel reprocessing and recycling as advanced reactor designs move forward.

INTRODUCTION

The origins of nuclear power are closely tied to fuel reprocessing. Multiple countries have pursued reprocessing, particularly the conventional PUREX method, as a spent nuclear fuel (SNF) management tool. However, the separation of plutonium– which the International Atomic Energy Agency considers a direct-use material for nuclear weapons – during the process raises significant nonproliferation concerns.[1] Historically, these concerns, along with significant cost challenges for reprocessing plants, have resulted in global resistance to reprocessing. Today, reprocessing is being discussed as a host of emerging or "advanced" reactor designs propose to use unconventional reprocessing or recycling techniques in their fuel cycles. Using the case studies of the United States and Canada, two early proponents of nuclear power, this paper examines the historical trends and changes in reprocessing policies to glean insight into the factors that might influence anti-reprocessing policies to change to support proposed advanced fuel cycles. For these two countries, nonproliferation concerns have consistently influenced the discussion on reprocessing, indicating that future recycling techniques will have to demonstrate high levels of nonproliferation assurance to influence any flexibility or changes to policies prohibiting reprocessing.

REPROCESSING

The global resurgence of non-light water reactor (LWR) designs, generally called Generation IV reactors, has increased interest in "recycling" spent fuel for better uranium resource management and solutions to the ever-growing global SNF inventory.[2] Many emerging reactor developers want to use their designs to help resolve enduring concerns about nuclear power including safety, cost effectiveness, and waste management. As a result, there are multiple designs that explicitly are intended to accompany a closed fuel cycle, through passive chemical processing (as in a molten salt reactor), an external process at a small unconventional reprocessing facility (such as pyroprocessing), or an external conventional reprocessing system.

The greatest concerns related to conventional reprocessing are nuclear weapons proliferation and cost. Separated plutonium at a reprocessing plant can be an attractive target for non-state actors looking to steal direct-use material, or for a State seeking to divert plutonium towards weapons. For this reason, physical protection measures and international safeguards activities at reprocessing plants are extensive. For example, Japan is a non-nuclear-weapon State (NNWS) with a Comprehensive Safeguards Agreement (CSA) and Additional Protocol (AP) with the International Atomic Energy Agency (IAEA). Its Rokkasho Reprocessing Plant has had a 24-hour IAEA inspector presence and over 1200 person days of inspection of installation efforts and Safeguards inspection activities since 2006 when commissioning began.[3] Regarding costs, multiple studies have shown that conventional reprocessing of LWR fuel is more expensive than direct disposal of SNF.[4] Accordingly, many national policies have phased out reprocessing due to these concerns. When asked about the potential proliferation challenges of reprocessing and recycling fuel, some emerging reactor developers have noted that they would leave minor actinides with plutonium and uranium during separation, making it harder to solely extract plutonium and distancing the processes from conventional reprocessing.[5] However, the exact processes are not publicly determined yet, making it difficult to anticipate the extent of nonproliferation challenges and measures at such facilities.

States have pursued the separation of plutonium and uranium from other materials in SNF for a variety of national policy goals beginning with the United States' plutonium production for weapons at the Hanford site B-Reactor as early as 1944.[6] B-Reactor supplied plutonium for the U.S. weapons program, but reprocessing can also produce reusable fuel for civilian nuclear energy. The most used reprocessing method has been hydrometallurgical PUREX, where fuel rods are chopped and dissolved in nitric acid before further purification.[7] While reprocessing is not widely pursued, with most nuclear power countries opting for open fuel cycles, the countries that have had reprocessing policies have mostly been significant nuclear energy (and spent fuel) producers. Specifically, 8 countries (US, UK, Russia, Japan, India, Germany, France, and Belgium) have operated reprocessing facilities while Japan and China intend to begin operating new reprocessing facilities in the next several years.[8] 16 countries have at some time reprocessed their own fuel, either domestically or abroad.[9] Now, however, only a fraction of those countries continue to reprocess due to cost and proliferation concerns.

In recent years, designs that include recycled fuel have begun moving forward despite long-held national policies against reprocessing. For example, Moltex is undergoing the Pre-Licensing Vendor Design Review process for its Stable Salt Reactor – Wasteburner (SSR-W) in Canada, which has an

established open fuel cycle policy.[10] The ARC-100 sodium-cooled fast SMR could recycle its waste and is under development in both the U.S. and Canada.[11] The extent to which States with a once-through policy are willing to change to accommodate their interest in emerging reactors has yet to be seen. Factors including economic considerations and the prioritization of nonproliferation to a government seem to play a role in determining reprocessing policy, with nonproliferation remaining a constant consideration.

The cases of U.S. and Canadian reprocessing policies represent a wide spread of approaches to nuclear energy: one nuclear-weapon state (NWS) and one NNWS, one LWR user and one pressurized heavy water reactor (PHWR) user, one with a changing reprocessing history and one with a more consistent resistance. The historical trends in reprocessing policies in the two following case studies attempt to shed light on the conditions under which a State might adapt its fuel cycle policy in the face of emerging interest in unconventional recycling.

Fig. 1: Comparison of U.S. and Canada Nuclear Power and Fuel Recycling Profiles

Country	Primary Reactor Type	Nuclear Weapons? (Y/N)	Number of Operational Power Reactors*	Nuclear Electricity Production Share in 2020 (%)	Examples: Designs Under Development With Proposed Recycling
United States[12]	LWR	Y	93	19.7	ARC-100
Canada[13]	PHWR (CANDU)	N	19	14.6	SSR-W; ARC-100

*As of July 2021

CASE STUDY 1: THE UNITED STATES' REPROCESSING HISTORY AND INFLUENCE OF ADVANCED FUEL CYCLES

Costs and proliferation concerns have been the primary drivers of reprocessing policy in the United States. In the early days of nuclear energy, the United States primarily wanted plutonium production for its weapons program, but President Eisenhower's "Atoms for Peace" program prioritized civil nuclear energy.[14] The introduction of commercial reprocessing came with the Atomic Energy Commission's (AEC) 1956 attempt to encourage private industry to reprocess spent fuel through a program of cost assessment seminars and other tools.[15] Dr. W. Kenneth Davis of the AEC emphasized that the program supported the need for competitive nuclear power driven by industry at all stages of the nuclear fuel cycle.[16] Large-scale commercial reprocessing began a decade later. In 1966 Nuclear Fuel Services, Inc. opened a reprocessing facility with a capacity of 300 metric tons per year throughput of AEC-owned material and commercial spent fuel in West Valley, New York.[17] Until its closure in 1972 the plant reprocessed 640 MT of fuel.[18] General Electric and Allied-General Nuclear Services also pursued plants in the 1960s and 1970s, but neither commercially operated due to operations problems and delays.[19]

The U.S. then entered a period of nonproliferation-focused policy and a move away from reprocessing, particularly in response to India's 1974 "Smiling Buddha" nuclear test.[20] In 1976 President Ford stated based on the Nuclear Policy Review Group's report that "I have concluded that the reprocessing and recycling of plutonium should not proceed unless there is sound reason to conclude that the world community can effectively overcome the associated risks of proliferation. I believe that avoidance of proliferation must take precedence over economic interests."[21] In 1977 President Carter elaborated on Ford's statement and suspended commercial reprocessing in order to attempt to provide a global example of nonproliferation efforts.[22] This suspension extended to international nuclear cooperation agreements when the Nuclear Nonproliferation Act of 1978 required that NNWS engaging in peaceful nuclear cooperation with the U.S. must not develop new reprocessing capabilities.[23] The act also encouraged pursuit of "alternatives to an economy based on the separation of pure plutonium."[24]

President Reagan reversed the previous two administrations' resistance to reprocessing when he came into office in 1981, citing the policy decision as an example of over-regulation deterring utilities from pursuing nuclear power:[25]

> "I am lifting the indefinite ban which previous administrations placed on commercial reprocessing activities in the United States. In addition, we will pursue consistent, long-term policies concerning reprocessing of spent fuel from nuclear power reactors and eliminate regulatory impediments to commercial interest in this technology, while ensuring adequate safeguards."[26]

This approach was aligned with Reagan's domestic economic policies, while still preserving his interest in nonproliferation. The above quote refers only to domestic reprocessing, leaving the suspension on reprocessing in NCAs intact. President George H. W. Bush, on the other hand, stated that the U.S. would not reprocess SNF and prohibited a reprocessing agreement between the Long Island Power Authority and COGEMA (France).[27] This was followed by President Clinton's 1993 statement discouraging industry from pursuing reprocessing in the U.S.[28] This stance was corroborated by a 1996 National Academies of Science report that found reprocessing was too costly for the U.S.[29]

The shift towards encouraging unconventional reprocessing came with President George W. Bush's 2001 National Energy Policy Development Group report.[30] In it, senior members of the administration recommended that:

> "…in the context of developing advanced nuclear fuel cycles and next generation technologies for nuclear energy, the United States should reexamine its policies to allow for research, development and deployment of fuel conditioning methods (such as pyroprocessing) that reduce waste streams and enhance proliferation resistance. In doing so, the United States will continue to discourage the accumulation of separated plutonium, worldwide."[31]

The report also recommended that "The United States should also…develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste intensive, and more proliferation-resistant."[32] President Bush's Global Nuclear Energy Partnership initiative (GNEP) assessed alternative fuel cycles domestically and advanced commercial reprocessing research for several years.[33] In 2009 its programmatic environmental impact statement component was cancelled by the Obama administration's Department of Energy, perhaps due in part to the Government Accountability Office's conclusions that the proposed technologies were not ready for commercial development, nor would they sufficiently resolve nuclear waste and proliferation issues.[34] The Obama administration's fuel cycle efforts were largely centered around SNF disposal given the stalled Yucca Mountain project.

Recently, advanced recycling technologies have been a government focus along with efforts to develop advanced reactors. The 2017 Nuclear Energy Innovation Capabilities Act, which passed Congress with bipartisan support, included provisions building on the 2005 Energy Policy Act's Advanced Fuel Cycle Initiative, showing a return to the Bush-era interest in advanced reprocessing.[35] This law was just one example of U.S. policy displaying flexibility regarding closed fuel cycles during President Trump's administration. Under President Biden, the interest in alternative fuel cycle research has continued; for example, the Advanced Research Projects Agency – Energy is funding a program examining, among other things, recycling technologies.[36] In August 2021 the Nuclear Regulatory Commission (NRC) announced it will not pursue new licensing rulemaking for commercial reprocessing facilities due to industry lack of near-term (within ten to twenty years) interest.[37] This change leaves open the possibility of future reprocessing facility-specific licensing rules but indicates that licensing these facilities is not a priority at present.

CASE STUDY 2: CANADA'S REPROCESSING HISTORY AND INFLUENCE OF ADVANCED FUEL CYCLES

Where the national U.S. policy has shifted between encouragement and discouragement of fuel reprocessing, Canada's policy has consistently kept the fuel cycle open. While bench-scale work on recycling technologies, for reprocessing of LWR fuel or others, continues, there has been no commercial reprocessing.[38] It is important to note that, unlike the U.S., Canada is a NNWS with a CSA and AP, which intensifies the application of safeguards domestically and means that parts of the fuel cycle are restricted under its nuclear cooperation agreement with the U.S. Also notable is the dominance of CANDU pressurized heavy water reactors in Canada's fuel cycle; the different fuel specifications from the U.S.'s light water reactors change the uranium resource utilization assessment for an open fuel cycle. Therefore, uranium resource considerations and international nonproliferation commitments are the pivotal parts of Canada's reprocessing policy.

Canada's first reactor went online in 1962 and commercial operation began in 1971.[39] Global proliferation concerns heightened in 1974 with India's nuclear test, leading Canada to adopt a nuclear export policy with announcements in 1974 and 1976 of significantly more rigid nonproliferation components "because it wants to be assured that any reprocessing of Canadian nuclear material would take place as an integral part of a significant nuclear energy program and

that effective technical, institutional and safeguards measures have been put into place to ensure that there is no misuse of the separated plutonium."[40]

The resource utilization consideration was noted in 1977, when Atomic Energy of Canada Limited (AECL) Chairman Ross Campbell noted, "we have sufficient uranium reserves to see us past the turn of the century at our projected nuclear growth of 83,000 MWe by 2000, using the present once-through natural uranium cycle."[41] In addition, as of 2010 CANDU fueling costs were two times lower than those of other reactors and the U-235 concentration in the natural uranium CANDU fuel is also decreased.[42]

In the early 1990s AECL began research with the U.S. Department of State, the Republic of Korea's Korea Atomic Energy Research Institute (KAERI), and the IAEA into an experimental dry processing technique called DUPIC or "Direct Use of Spent PWR Fuel in CANDU."[43] It proposed fabricating CANDU bundles from spent pressurized water reactor fuel without separation.[44] In 1997 Canada's Department of Foreign Affairs and International Trade requested and received agreement from the U.S. for Canada to use the technique.[45] The research teams made progress in determining economic, quality, performance, and fabrication feasibility, and research into further DUPIC development is ongoing.[46] Despite some arguments that DUPIC is different enough from conventional reprocessing to be considered less of a proliferation risk, the request under reprocessing authorization requirements demonstrates that wariness about nonproliferation is not likely to be easily shifted to allow innovative reprocessing until a sound demonstration produces buy-in domestically and internationally.[47]

Since 2002, the Nuclear Waste Management Organization (NWMO) has been tasked by the Nuclear Fuel Waste Act to manage waste with a focus on irradiated fuel direct disposal.[48] The Act requires NWMO to carry out a study on waste management focusing on disposal or storage as the primary management option, rather than reprocessing.[49] While disposal could still be relevant for the high-level wastes resulting from reprocessing, this mandate corresponds to prioritizing SNF disposal without separation or other recycling. NWMO's website states that "There is currently no plan to recycle Canada's used nuclear fuel on a commercial scale."[50] National Resources Canada is also conducting a review of the Radioactive Waste Policy Framework, but the review does not specifically consider the inclusion of reprocessing or recycling.[51] At the same time, the Canadian government is keeping abreast of developing recycling. Notably, Canadian Nuclear Laboratories (CNL) is working with Moltex Energy and other partners to pursue Moltex's proposed recycling technology.[52] The Canadian government also provided over 50 million Canadian dollars to Moltex's SSR-W design development, indicating interest in researching such a process even if the policy does not yet account for advanced reprocessing.[53]

CONCLUSION: PROSPECTS FOR A RE/TURN TO REPROCESSING

The two cases explored above show a range of stances on reprocessing dependent on national fuel cycle needs and perceptions of global influence. The U.S. has historically prioritized global

leadership in nuclear energy technology and nonproliferation. Even when the policy has shifted more towards closing the fuel cycle for market reasons, the importance of nonproliferation remains. The extent to which alternative recycling technologies could address both market and nonproliferation considerations is still unknown. Adequately ensuring a standard of nonproliferation practice for a new reprocessing or recycling technology will be a gradual process, as will cost optimization, but some closed-cycle reactors are already undergoing discussions with regulators.[54] The reprocessing policy is therefore unlikely to change prior to the first commercialization of reactors associated with closed fuel cycles. For reprocessing to be reintroduced into the national policy, an adequate domestic demonstration of both feasible economics and proliferation risk reduction would be needed.

Similarly, in Canada the current open fuel cycle is the most economically sensible. With Canada's geological disposal facility under development as well, closing the fuel cycle would have few advantages for resource availability or proliferation concerns at this time. Unless all of Canada's current reactors are replaced with advanced non-water-cooled reactors with closed fuel cycles, significantly changing the country's nuclear resource utilization, the threshold for acceptance of a closed fuel cycle is high.

It is important to note that nonproliferation considerations do vary between the U.S. and Canada. Canada, as a NNWS, must ensure that a reprocessing policy meets its international obligations as well as its domestic objectives. Therefore, international acceptance of a policy change on reprocessing, particularly from its NWS partners like the U.S., would have a direct impact on Canada's agreements. On the other hand, the U.S.'s status as a NWS means that measures including its safeguards agreement with the IAEA are voluntary. Therefore the U.S. international nonproliferation incentive comes from its perceived position as a model for global nonproliferation.

The above does not mean that reactors like the ARC-100 or SSR-W will never be deployed; rather, their deployment, if they do reach commercialization, will likely precede the acceptance and deployment of their associated closed-cycle facilities and processes. With the U.S. NRC's August decision, Canada is poised to be one of the first countries to consider the licensing of such facilities.

These cases have shown that domestic and international nonproliferation expectations have played a significant role in reprocessing policies. Underlaying market considerations is the need for nonproliferation responsibilities to be maintained, both for the international community and bilateral relationships. While these two cases cannot be generalized to all States, they represent a spread of approaches to nuclear energy and may indicate the strategic considerations other countries face as they consider new reactors with advanced reprocessing components. There are undoubtedly other factors impacting reprocessing decisions which should be explored in more depth, but these case studies indicate that economic and nonproliferation considerations will likely continue to be key factors influencing changes in reprocessing policies.

ACKNOWLEDGEMENTS

This work is part of the Stimson Center Nuclear Safeguards Program's "Back-End to the Future" project examining the ways emerging technologies and evolving safeguards obligations affect nuclear safeguards at the back-end of the nuclear fuel cycle. The project is made possible by the generous support of the John D. and Catherine T. MacArthur Foundation. The author thanks Dr. Cindy Vestergaard for her guidance and review.

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