Nuclear Fuel Cycle Choices and Security: A Decision Analysis Approach

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This paper starts with the fundamental premise that nuclear security cannot be evaluated in isolation to other types of security and political power, including energy security, economics, domestic politics, and international influence and prestige. Moreover, I employ a broad based definition of nuclear security. What I mean is that this paper considers aspects of nuclear security beyond the International Atomic Energy Agency's definition of "the prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances, or their associated facilities." While this definition is essential in clearly stating the goal of controlling nuclear material and other radioactive substances, it does not encompass a state's need to feel secure against nuclear attack from another state. Thus, an expanded definition of nuclear security involves the concepts of deterrence against nuclear attack and improvement of the international nonproliferation system in order to strengthen the norms against the spread of nuclear weapons and detonation of these weapons. Consequently, I argue that examining a state's assessment of the expanded scope of nuclear security is necessary to understand a state's choices about the nuclear fuel cycle.

To work systematically through this analysis, I will employ a decision analysis framework. This tool provides decision makers the capability to work logically and thoroughly through difficult decisions involving multiple objectives. I believe this analytic tool is very appropriate for assessing choices about the nuclear fuel cycle because of the multiplicity of factors and influences on this decision. Also, because this decision is not static, i.e., will change over time, an analytic framework that identifies the roles of all internal and external stakeholders is needed. Specifically, when a government makes a decision about nuclear policy, it will be influenced by public perceptions, business interests, views of allies, and practices of neighboring states, especially rivals and enemies.

Because of the multiple player aspects of this decision, one can think of the choices in terms of game theoretic methods. I argue that the choice of a nuclear power program and especially a decision about whether to pursue nuclear fuel cycle capabilities is a semi-cooperative game. In cooperative games, players make commitments to coordinate their strategies. Think, for example, of a prisoner's dilemma game in which each player can communicate with other players in order to determine an optimum result for all players. In non-cooperative games, players compete against each other and often do not know other players' strategies or may only have partial information about other players' strategies and intentions. For example, consider the scene in the movie *A Beautiful Mind* when John Nash has his insight that a group of men going to introduce themselves at the same time to an attractive woman prevent each other from achieving their desired goal: a date with the woman. Here, the Nash equilibrium is that no one achieves his goal, but in a subsequent turn of the game, a lone actor such as Nash has an opportunity to introduce himself to the woman. In a semi-cooperative game, players can form alliances and thus cooperate with some other players but not all players. In geopolitics, there will be coalitions of like-minded states, but these alliances will leave out other states for reasons of ideology and competition for scarce resources.

Similarly, decisions about nuclear security and nuclear fuel cycle choices involve semi-cooperative games. As witnessed by past development of nuclear power programs, some states have decided to rely on the international market for provision of all their fuel needs and thus have not developed enrichment or reprocessing facilities. While a market involves competition, the suppliers and clients have a vested interest in negotiating prices that will generally lead to continued contracts to purchase nuclear fuel. Thus, those client states will remain happy to maintain these business relationships as long as they are assured of reasonable prices for and timely delivery of the fuel. Other states, however, have made different assessments based on resource scarcity or the nuclear fuel cycle practices of their neighbors or major powers. To underscore the dynamic nature of this decision process, certain states that had proceeded down the first path of not developing enrichment and reprocessing facilities may later reevaluate and choose the fuel cycle development path due to changing behavior of neighbors, expanding nuclear industry, growing concerns about the reliability of fuel supplies from the international market, or increasing wariness about nuclear weapons development in their region.

The remaining sections of this paper describe briefly the major current nuclear fuel cycle choices, define the categories of nuclear material from a weapons-usability perspective, and then provide an analysis of a state's decision factors. The final sections discuss the direction of future research that would create a rigorous decision matrix that decision makers can use to make quantitative assessments.

Nuclear Fuel Cycle Choices

A state has several options for a nuclear power program. A fundamental need is to ensure that there is sufficient fuel for a state's nuclear power plants. A state is not required to produce its own fuel as long as there are readily accessible supplies at competitive prices, as mentioned above. Thus, because many nuclear power producing states are confident that the international fuel market works well, they have chosen to not pursue development of nuclear fuel cycle capabilities.

There are multiple nuclear fuel cycles. Here, I will briefly describe the currently practiced cycles; I will not discuss the thorium cycle, for instance, although this may show significant promise in the future especially because of the abundant global thorium resources and the proliferation-resistance that thorium cycles may offer. The most commonly chosen nuclear fuel cycle is called the once-through uranium cycle because it uses each uranium-based fuel assembly once in a reactor and then the irradiated or spent fuel assembly is taken from the reactor and stored.

This cycle has two options. The first, most commonly pursued option is to enrich natural uranium to low enriched amounts (typically 3 to 5 percent in the fissile isotope uranium-235). (Fissile means that the material tends to easily fission when it absorbs a neutron of almost any energy level, i.e., either slow or fast moving neutrons.) This enriched uranium option obviously requires one or more enrichment plants in the world. If demand for enriched uranium goes up, so will the need for expanded capacity of existing enrichment plants or the construction of new plants. Low enriched uranium (LEU) fuel is used in hundreds of light water reactors worldwide. Light water reactors can either be pressurized water reactors (PWRs) or boiling water reactors (BWRs). The second option in the once-through uranium cycle is to form nuclear fuel from natural uranium. This fuel is used in pressurized heavy water reactors (often of the CANDU--Canadian Deuterium Uranium--design) or graphite moderated reactors.

If a state wants to recycle the plutonium produced from uranium-based fuel, then reprocessing is required. Reprocessing is a chemical technique that allows extraction of plutonium, uranium, and other fissionable materials from spent fuel. (Inside uranium-fuelled reactors, the most abundant isotope uranium-238 is converted into plutonium-239, a fissile isotope. Within a relatively short period of time—days—after refueling, uranium-fuelled reactors derive part of their power from fission of plutonium.) Like the uranium-once-through-cycle, reuse of plutonium has different options. For countries that have reprocessing plants or that have contracts with reprocessing plants, they typically use the once-through recycling option in which the mixed oxide (MOX) fuel, which is a mixture of plutonium oxide and uranium oxide is only used once, that is, it is usually not reprocessed a second time. But multiple reprocessing is possible although it is typically not done because the material produced is not as desirable for reuse in light water reactors due to the increased concentrations of especially hazardous radioisotopes such as uranium-232 and uranium-236.

States that have invested in reprocessing plants have usually done so in order to build up a cache of plutonium for fuelling fast neutron reactors. These reactors could either be operated in a burner or breeder mode. In the former, the reactor would consume more fissionable material, and in the latter, it would breed more fissile material such as plutonium to increase the available supply. But fast neutron reactors are more expensive than thermal reactors such as light water reactors and have experienced technical challenges. Most estimates place commercial development of many fast reactors in the time period of mid-century or beyond.

There are many reprocessing techniques. The only one that is commercially practiced is PUREX, which extracts plutonium and uranium and completely separates them from highly radioactive fission products and other fissionable material such as americium, curium, and neptunium. Research is being done on techniques that may offer proliferation-resistant benefits. These techniques include pyroprocessing, UREX+, and DUPIC (Director Use of Spent PWR Fuel in CANDU). Such techniques would not separate pure plutonium. They would produce a mixture of plutonium with other materials in order to reduce the desirability of the mixture for weapons purposes. The concern remains though that this mixture may be diverted to a clandestine processing facility to extract pure plutonium. Thus, there is still a need for adequate safeguards on "proliferation-resistant" reprocessing facilities.

Categories of Nuclear Material and Weapons Usability

Nuclear weapons have traditionally used two types of fissile material: highly enriched uranium (HEU) and weapons-grade plutonium (Pu). (Here, I say "traditionally" because there are other weapons-usable fissile materials including uranium-233, americium-241, and neptunium-237. But these materials are far less abundant than HEU and the fissile isotope plutonium-239 and thus will not be considered in this paper. Nonetheless, future fuel cycles employing thorium may raise concerns about the availability of uranium-233, which is formed from fertile thorium-232.) HEU is defined as a mixture of uranium containing 20 percent or more of the fissile isotope. Weapons-grade plutonium has less than six percent Pu-240 and other non-Pu-239 isotopes.

The proliferation potential of a nuclear material depends on the isotopic content, the degree to which the material is embedded within a mixture of highly radioactive materials, the physical protection measures employed, and the extent to which safeguards and monitoring are applied. From the standpoint of isotopic content, the greater the proportions of uranium-235 in HEU or plutonium-239 in plutonium, the more attractive the material is for weapons purposes. Bruno Pellaud has defined various categories of weapons usability. Category 1: "Practically unusable"; Category 2: "Conceivably usable"; Category 3: "Practically usable"; Category 4: "Standard material"; and Category 5: "Best quality."[1] Spent fuel is considered category 1 material because of the presence of highly radioactive fission products that provide a lethal barrier against theft of the embedded plutonium. Separated plutonium that has a high percentage of non-Pu-239 isotopes is usually considered category 2. For lesser amounts of these isotopes, the plutonium mixture can be considered category 3, depending on the burn up of the spent fuel. Higher burn up material tends to have greater amounts of non-Pu-239 isotopes depending on the operation of the reactor. This will typically be the case for once-through recycling. Multiple recycling of plutonium will further lessen the attractiveness of the resulting plutonium mixture and will tend toward category 2 material. Breeder reactors could readily be used to produce category 4 and 5 materials; thus, these reactors can pose a proliferation concern. In principle, even light water reactors could be operated to produce weapons-grade or at least higher quality weapons-usable plutonium, but the typical commercial operation would produce reactor-grade plutonium that while weapons-usable is not very desirable for weapons purposes. These reactors can be relatively easily monitored in that they would have to shut down in order to be refueled. In contrast, heavy water reactors are a greater proliferation concern because of their refueling during operation and the higher quality of plutonium that can be produced during their operation. In sum, the choices states make in terms of types of reactors,

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[1] Table I in B. Pellaud, *Proliferation Aspects of Plutonium Recycling,* Journal of Nuclear Materials Management, Fall 2002, Volume XXXI, No. 1

operation of those reactors, and whether or not to reprocess can make a big difference for the availability and weapons-usability of the fissile material used and produced.

Decision Factors and Analysis

In this section, I outline various decision factors that would likely be considered in states with nuclear power programs. I emphasize that this list is most probably not complete and instead is intended to stimulate discussion and a more thorough future analysis as outlined later. These decision criteria are not presented in any particular order.

- Number of nuclear power plants: A commonly heard argument is that a country cannot economically justify construction of fuel cycle facilities, especially uranium enrichment, until it has eight or more large power reactors.
- Investment in enrichment and/or reprocessing: A country may have sunk costs into such facilities and thus would be reluctant to abandon them and may also use past expenditures to justify expansion of these facilities if they are economically viable or fit within the vision of a country's real or perceived energy security needs. States with substantial uranium resources but with no nuclear power program may decide to build enrichment facilities to add more economic value to their indigenous uranium.
- Adherence to the Nonproliferation Treaty, safeguards agreements, and Convention on Physical Protection of Nuclear Material: How well established and committed is the state to the nonproliferation system and concerning safeguards, has the state implemented the Additional Protocol to comprehensive safeguards?
- Security alliances: Is the state part of a security alliance receiving protection from one or more nuclear-armed allies?
- Conditions of nuclear energy cooperation agreements: Do these agreements prohibit or forego enrichment and reprocessing or do they allow for such activities under mutual consultation?
- Political statements concerning pursuit of enrichment or reprocessing: Have a state's leaders made statements for or against these activities?
- Presence of neighboring states enrichment or reprocessing facilities: Do neighboring states have these facilities; if so, which ones and why were they pursued?
- Resources availability: Does the country have access to relatively plentiful fossil fuel resources for electricity generation? These resources could be indigenous or from trusted supplier states. Are these resources inexpensive compared to nuclear power?
- Public support for nuclear power: How supportive is the public about nuclear-generated electricity?
- Public support for nuclear waste management: Even if the public is generally supportive of nuclear power, it may be largely opposed to nuclear waste storage? This opposition may drive decision makers to consider reprocessing

or other options that would alter the perceptions surrounding permanent repositories.

- Degree of central government ownership of utilities: Who holds the real financial power in terms of electricity generation? Can the federal government push through decisions to build nuclear power plants or nuclear fuel cycle facilities?
- Level of enthusiasm among nuclear scientists and engineers for fuel cycle facilities: Do technical people have enough political power or influence on those who have the political power to argue for or against these facilities?
- Time scale for nuclear energy planning: Is it focused on the next few years or it is focused over many decades? For the former, investments need to deliver results quickly and thus would discourage building fuel cycle facilities. For the latter, a state may be willing to wait several decades for an investment to pay off. In that situation, reprocessing, for example, could look like a strategic investment to hedge against possible future uranium fuel shortages.

There are likely other factors to consider. These can be identified through interviews as discussed in the next section.

Toward a Decision Matrix and Future Work

This paper is a preliminary work in that it does not provide a full decision matrix. In such a matrix, all relevant criteria would be listed on one axis and the options or choices along an orthogonal axis. The above section presents many of the criteria but some may have been missed. To make sure that all criteria have been included, analysts should perform surveys and detailed interviews with stakeholders. In addition, the criteria need to be weighted by their importance or priority. The weighting system would consist of a relative number scale say from 1 to 10, with 1 meaning the lowest importance and 10 meaning the highest importance. As with determining the criteria, discovering the appropriate weighting for each criterion is best done with detailed interviews of stakeholders.

To determine the optimal choice, one sums over the weighted criteria. The highest score among the choices indicates the optimal choice.

Conclusion

This paper has outlined a decision analysis framework for thinking through decisions about nuclear fuel cycle choices and security. The paper started with the premise that there are multiple aspects to security. Thus, solely examining and planning for the security of nuclear materials is not sufficient to understand the choices states have made and will make concerning their nuclear power programs. This paper presents the author's views on relevant criteria for making these decisions. As indicated above, performing detailed interviews of all stakeholders is an optimal method for discovering criteria and appropriate weighting of the importance value of each criterion.