Non-Proliferation Merits of Combined Recycling-Transmutation of Nuclear Wastes

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INTRODUCTION

A recent report of the National Academies of Sciences, Engineering and Medicine (NASEM) addressed the topic of advanced reactor fuel cycle issues and concluded, with regards to potential recycling options, that "the once-though fuel cycle is the baseline, and any new fuel cycles should have advantages over that baseline for them to be deployed" (1).

Several recycling options can be considered to close the nuclear fuel cycle in a quest for a long-term stable and sustainable provision of energy. To address the considerations highlighted by NASEM, those closed cycle strategies have to be assessed on the basis of the attractiveness of the nuclear material not only during the recycling process but across the whole cycle until and including final disposal.

In this study, we have analyzed the evolution of the proliferation attractiveness of nuclear fuel over its lifetime, following the first irradiation, in different fuel cycle options. It appears that the combination of recycling and transmutation of non-separated higher actinides on a single site presents the most proliferation-resistant framework, even in comparison with the once-through baseline strategy. This option brings several advantages over the open cycle, including long-term proliferation resistance and more manageable application of safeguards in a long-term perspective.

QUANTIFICATION OF THE ATTRACTIVENESS OF USED FUEL AND EVOLUTION IN DIFFERENT FUEL CYCLES

The metrics adopted to assess the attractiveness of spent fuel at different stages of its lifetime in different fuel cycles is provided by the internationally accepted "Estimated material conversion times for finished Pu or U metal components" reported in Table 1 of Ref (2), as well as in Box 6.1 of Ref (1). It is based on the assumption that all material containing fissile material could be used for the production of an explosive device, with relative attractiveness measures based on the time required to convert the material to the metallic components of a nuclear explosive device. It is assumed that the potential proliferator has no constraints in terms of financial or technical capabilities. Even though the absolute values of time reported depend on a wide variety of factors, their relative difference is seen as relevant.

The conversion times reported in (2) are provided as ranges of time. However, explanations in the text and footnote highlight that the low and high-ends of the ranges refer to different levels of purity of the material reported. In this regard, we can assign specific values of conversion time for the different forms of material in the back-end of fuel cycles as reported in Table I.

TABLE I. Estimated conversion time for different materials in the back-end of different fuel cycle options

Material in back-end of fuel cycle	Estimated conversion time
Chemical compound containing purified plutonium	1 week
Chemical compound containing impure plutonium, separated from fission products	3 weeks
Irradiated fuel, with no dilution or specific stabilization step	1 month
Conditioned irradiated fuel	3 months
Spent fuel depleted from plutonium	12 months

Note that we do not consider here that conditioned spent fuel could be labelled as "unrecoverable" as in the wording of so-called "retained waste" in Ref (2). This wording is a pragmatic framework to allow the termination of physical verification of inventories for long term disposal, but does not refer to an actual removal of the proliferation risk. This is supported by the statement in the NASEM report that "Chemical means of reducing attractiveness cannot render a nuclear material entirely useless for a weapon but can only increase the time an adversary would need to convert the material into a more usable form" (1). This statement supports the use of estimated conversion time as metrics of attractiveness, as well as the continued consideration for this metrics over very long storage times, even in deep repositories. Even if retrieval activities of material in geological repositories are deemed to increase the overall conversion time, this time increase would be similar for all types of material ultimately disposed, so the relative attractiveness metrics remains relevant even at this stage of the fuel cycles.

We can cross-check the relevance of the attractiveness metrics reported in Table I with the categorization of nuclear materials established for the purpose of nuclear security and reported in Table 1 of Ref (3). According to this categorization, plutonium without the protecting nature of a strong radiation field is category I, irradiated material, whatever its chemical composition, is category II and material in which the primary fissile material is uranium is category III if it is enriched to less than 10 % or not categorized if it is natural or depleted uranium. This can be summarized in Table II for materials identical to those reported in Table I.

TABLE II. Nuclear security categories of different materials in the back-end of different fuel cycle options

Material in back-end of fuel cycle	Category
Chemical compound containing purified plutonium	I
Chemical compound containing impure plutonium, separated from fission products	I
Irradiated fuel, with no dilution or specific stabilization step	II
Conditioned irradiated fuel	II
Spent fuel depleted from plutonium	III or less

Immediately after irradiation and during on-site temporary storage, spent fuel has an estimated conversion time of one month and a security category II according to metrics in tables I and II respectively, irrespective of the fuel cycle option.

In an open cycle, the conditioning of the wastes for long-term storage decreases the relative proliferation attractiveness of the material by increasing the estimated conversion time to three months. This is highlighted on Figure 1, where the attractiveness metrics described previously are reported in function of the evolution of the lifetime of the spent fuel material. The waste is then transported to a central storage facility (before or after conditioning), and possibly transported again to a final repository. On the very long term, the relative attractiveness of the waste increases due to decay of the radioactivity of fission products and the fact that "the self-protecting nature of spent fuel will eventually disappear over an extended period of time" (1).

In the classical approach of a closed fuel cycle (centralized production of MOX with purified Pu following reprocessing of spent fuel, and distribution across a fleet of reactors), the recycling of spent fuel decreases the estimated conversion time from one month to one week, thereby increasing its attractiveness (Figure 1). The recycled fuel, containing purified plutonium and from which the protective nature of the radioactive fission products has been removed, is transported to different reactors where it could be irradiated again. This irradiation rebuilds the radioactive inherent protection, and the conditioning of the wastes at the end of the cycle brings the material to a level of attractiveness comparable to the conditioned wastes of the open cycle, although possibly lower and for a longer period due to the less attractive isotopic composition of the plutonium after more than one irradiation cycles.

Fast neutron reactors optimized for burning actinides, combined on an integrated site with fuel recycling capabilities, represent an alternative approach of fuel recycling. This could for example be a molten salt reactor with online recycling (depending on the requirements for their initial core load). This will definitely be the case for the Stable Salt Reactor – Wasteburner (SSR-W) currently developed by Moltex, associated with a dedicated WAste To Stable Salt (WATSS) recycling facility, an integrated plant fueled by legacy wastes from currently operating reactors. The first-of-a-kind will be built on the site of the currently operating Point Lepreau Nuclear Generating Station (PLNGS) and is designed to use the CANDU spent fuel present on site as feed material over its entire operational life.

Fast reactors can accommodate fuel with significant quantities of minor actinides and other impurities, so recycling options that do not lead to purified plutonium can be used. Actually, it would not be practically or economically feasible to associate a genuine full-scale reprocessing plant to a reactor in an integrated framework. The product of the recycling process is therefore associated with a conversion time corresponding to three weeks according to Table I, slightly lower than the time of one month for the unprocessed spent fuel. The difference of attractiveness between purified and impure plutonium reflects the fact that although the technical barrier to proliferation provided by the radioactivity of fission products is largely removed, other barriers related to spontaneous neutron emission or heat generation remain (4). Besides, a fundamental difference with other fuel cycles is that this material remains confined in the integrated plant, already covered by comprehensive safeguards provisions until it is irradiated and the actinides are transmuted. After transmutation, the ultimate wastes are largely depleted of their original content of plutonium and the remaining nuclear material is essentially depleted uranium, for which the conversion time considerably increases to an estimate of 12 months. For the remaining lifetime of the ultimate waste, and especially during the security-critical chokepoints represented by long-distance transports and long-term storages, the attractiveness of the material remains considerably lower than similar wastes from other fuel cycle options. It does not even ultimately increase since the low level of attractiveness is due to the permanent removal of plutonium rather than the reliance on a protective barrier provided by mixture with radioactive material.

Other closed fuel cycles than the two options described previously can also be considered. We can for example consider the centralized production of recycled fuel with non-separated plutonium (with minor actinides and possibly other

contaminants still present). In which case the profile of the material attractiveness would follow an evolution comparable to the conventional reprocessing / MOX fleet scenario, although the minimum conversion time would be an estimate of three weeks rather than one. We can also consider the option in which a fleet of wasteburner reactors provide ultimate wastes depleted in plutonium, in which case the attractiveness at the end of the lifetime would drop to the level of the integrated recycling-transmutation option.

Overall, the two closed-cycle options reported previously and considered in Figure 1 represent the low and high ends of proliferation concerns possibly associated to closed fuel cycles in terms of attractiveness of material over the entire back-end of the process.

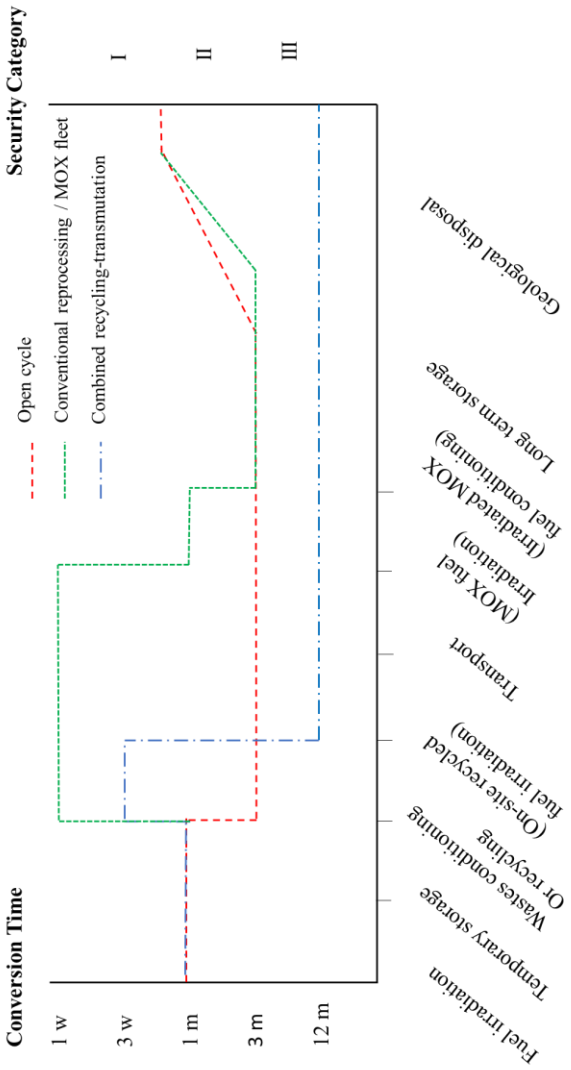

Fig. 1. Evolution of the metrics of material attractiveness for proliferation purposes in different fuel cycles. Process stages mentioned between brackets are only relevant for one of the fuel cycles considered.

In Figure 1 it is assumed that the waste treatment process (conditioning for the open cycle or recycling) is carried out at similar stages after fuel irradiation. Figure 2 accounts for the possible co-location of a combined recycling-transmutation plant with the production and temporary storage of spent fuel (as reported previously for PLNGS), whereas waste conditioning for a once-through option or reprocessing for a once-reuse of MOX would be at a centralized plant, to which it is necessary to transport spent fuel casks.

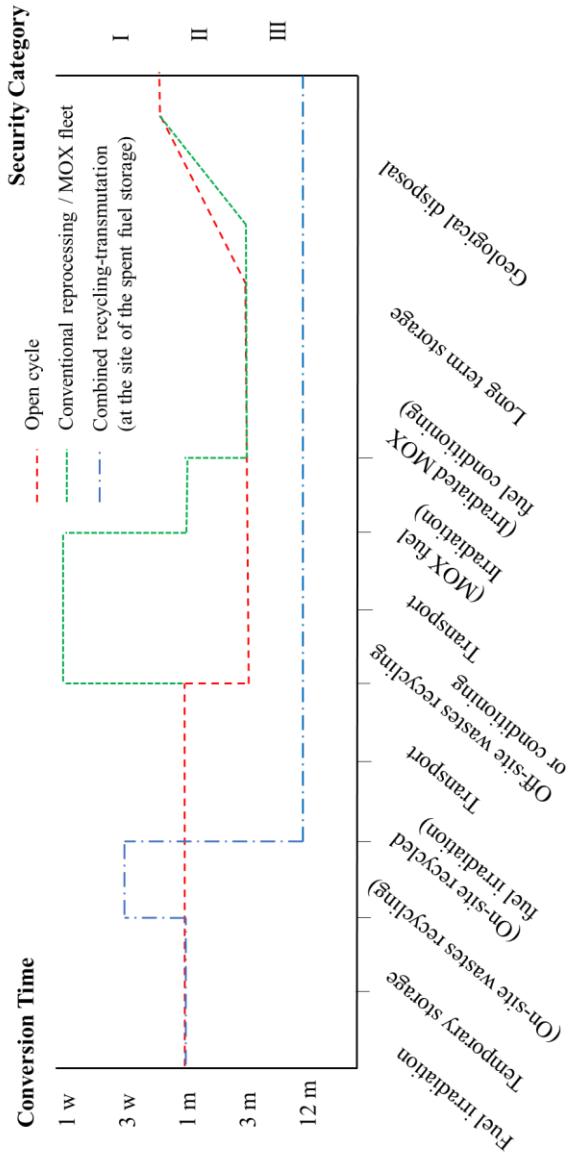

Fig. 2. Evolution of the metrics of material attractiveness for proliferation purposes in different fuel cycles. In this case the recycling-transmutation facility is co-located with the storage site of spent fuel, whereas spent fuel needs to be transported to a centralized plant (conditioning or reprocessing) in the two other options.

As highlighted in Figures 1 and 2, the proliferation concerns of the baseline option are not negligible and are actually higher than those related to some closed cycle options at different stages. This is especially the case at stages when safeguards provisions are the least effective and the material is the most vulnerable. Note that the conversion time is not at scale, which would have visually reduced the increase of conversion time at the recycling stage and would overwhelmingly be dominated by the considerable difference between the attractiveness of materials on the long term.

CONSIDERATIONS ON POTENTIAL DIVERSION OF RECYCLING TECHNOLOGIES

The IAEA report on "Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems" (5) identifies several proliferation resistance features for the different closed fuel-cycle options associated with innovative nuclear energy systems. In comparison, the only tradeoff reported for molten salt systems related to actinide burners is the "expansion of reprocessing activities". It is therefore important to assess this aspect in terms of actual proliferation concern.

The proliferation potential of different recycling technologies, including the technical challenges to convert a facility or to build a covert plant for the production of weapons-useable material, has been discussed elsewhere (4). It was assessed that technologies that do not lead to separated plutonium, and especially those based on pyroprocessing, do not represent a suitable proliferation route for countries that do not already have access to other separation technologies. And for countries that already have the financial and technical capabilities to develop and operate traditional reprocessing facilities, it would only bring a marginal change to their proliferation profile. In other words, the product of recycling processes that do not lead to purified plutonium would still have to be reprocessed, in a different facility with a different technology, to be usable for proliferation purposes. This is consistent with the assessment derived from Table 1 that impure plutonium compounds are only slightly more attractive than spent fuel, the feed material to the recycling process.

Fundamentally, it is assessed that, based on currently available authoritative definitions, plants based on technologies that do not lead to separated plutonium should not even be considered as "reprocessing facilities" (4).

KEY FINDINGS

It appears that, in accordance with the conclusions of the NASEM, a classical fuel recycling framework in which spent fuel would be reprocessed in a centralized facility and the recycled fuel, possibly including purified plutonium, dispatched to a fleet of reactors, would increase proliferation concerns.

It is also clear that the once-through open fuel cycle, although it is seen as the baseline, is not a perfect option. In comparison, alternative closed-cycle options, such as a combined recycling-transmutation process, bring considerable opportunities. The only trade-off is a slight decrease in the estimated conversion time at a specific time in the lifetime of the spent fuel, but only for a limited amount of time and in closed facilities already under control, so in the conditions where complementary safeguards measures are the most easily implemented. This is largely compensated by an inherent reduction of proliferation concerns for all the rest of the process steps, including the most critical steps of transport and very long-term storage. If it is assessed that technical provisions can suitably safeguard wastes in an open fuel cycle, this would be even more compelling with material permanently depleted of its most sensitive fissile components.

NASEM has wisely concluded that any new fuel cycles should have advantages over the baseline once-through fuel cycle for them to be deployed. We highlight here that the combination of recycling and transmutation in integrated facilities (as is for example the case for a Moltex WATSS – SSR-W integrated plant) represents the most promising framework for the consideration of a closed nuclear fuel cycle, a key to long-term sustainable energy production.

REFERENCES

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