VALUING FLEXIBILITY AND INTEGRATING RISKS IN USED NUCLEAR FUEL MANAGEMENT

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Abstract

As the first phase of the worldwide nuclear fleet is now approaching 40 years of operation, the Back end of the fuel cycle is becoming a forefront focus for utilities having to deal with pool saturation, reactor shutdowns, and requirements for extended periods of interim storage following significant deferral in the implementation of centralized interim storage or geological disposal facilities. As generated radioactive by-products are increasingly being seen as the Achilles heel of our industry, implementation of responsible used fuel management is a condition to ensure sustainability and expansion of nuclear as a low carbon energy source. Given the dynamic and uncertain market environment, cost of electricity and financial performance are not only important to historical utilities but are also key for the development of new capacities in large mature nuclear countries, expanding countries or new comers. In this context, Back end management with its long term liabilities and associated risks has a growing impact on utilities' financial performance and risk, development potential and market value.

Used fuel and related waste management requires an overarching long-term multi-dimensional system approach which is implemented in stages. A suite of options could be available over the long term, allowing integrating future informed decisions which provide safe, economic solution mitigating risks and uncertainties could be deployed.

Used fuel management system involves multiple decisions over time encompassing conflicts of drivers, uncertain factors and alternatives arising as the market or environmental conditions evolve. Uncertainty and risks are of different natures: technological, environmental, socio- political, economic and financial. Therefore, flexibility in back-end options offers mitigation for the uncertainty of risks. Valuing flexibility and integrating risks when assessing decisions will allow utilities and their stakeholders to decide which option to develop and when.

Orano, providing industrial and innovative back-end solutions and services for over 40 years, will share its developments allowing implementing various alternatives to manage used fuel matching a NPP-operator's specific financial cost and risk objectives.

1. INTRODUCTION

While safety of nuclear reactors and their economic competitiveness are strong drivers for the sustainability of nuclear power, management of used fuel and waste are increasingly critical as it concentrates a very wide spectrum of stakes, from non-proliferation and security to long-term safety, through environmental impact and public acceptance. As the first phase of the worldwide nuclear program, started in the 1980's, is now approaching 40 years of operation, the Back end of the fuel cycle is becoming a forefront focus for utilities having to deal with pool saturation, reactor shutdowns, requirements for extended periods of interim storage mainly dry storage at reactor site following significant delays in implementation of centralized interim storage or geological disposal facilities.

Pressure around used fuel management will increasingly grow, considering the current volumes of already unloaded fuel, and the strong expected growth of both used nuclear fuel inventories from operating plants and shutdown reactors in the coming decades.

Factors to take into consideration are of different natures: technological, environmental, safety and security regulations, public preoccupations and economic & financial.

Given the dynamic and uncertain market perspectives, cost of electricity and financial performance are not only important to historical utilities but also key for the development of new capacities whether in large mature nuclear countries, expanding countries or new comers. Deferral of decisions leading to extended storage

of used nuclear fuel at reactor sites could become a major impediment to the future expansion of nuclear energy due to the inability to implement a comprehensive management solution for spent nuclear fuel from existing reactors.

In this context, Back end management with its long term liabilities and associated risks has a growing impact on utilities' financial performance, development potential and market value.

2. USED FUEL MANAGEMENT OPTIONS

Used nuclear fuel management related to the production of nuclear-based electricity is a major challenge requiring a long-term strategic planning including technical plans and methods for the financing of all future actions. It is therefore and rightly so, the subject of special attention requiring a rigorous road map framed by nuclear national law or even transnational such as the European Directive of 2011 for the responsible and safe management of spent fuel and radioactive waste.

So far three different strategies have been adopted for used fuel management:

— "Closed fuel cycle", where the spent fuel is reprocessed and separated reusable materials recycled in nuclear reactor: this strategy has been partially implemented, i.e. mon-recycling of Pu and RepU at industrial scale in various countries. One third of the worldwide discharged fuel so far has been reprocessed [1].
— "Open fuel cycle", where the spent fuel is considered as a waste and is stored on an interim basis pending the availability of geological repository.
— "Wait-and-see or deferral of decision", where no decision has yet been made on a final disposition option and where used fuel is placed in interim storage

Both open and closed cycle solutions can be considered as sustainable options for used fuel management as they cover all the steps: interim storage in dry or wet solutions, transport, recycling (for utilities/counties having chosen the closed cycle), and final disposal of waste in deep geological repositories.

After 40 years of worldwide experience of the nuclear industry in trying to implement deep disposal repositories, none are yet fully constructed nor operational, although a few countries are making significant progress towards opening a repository, most notably Finland, Sweden and France.

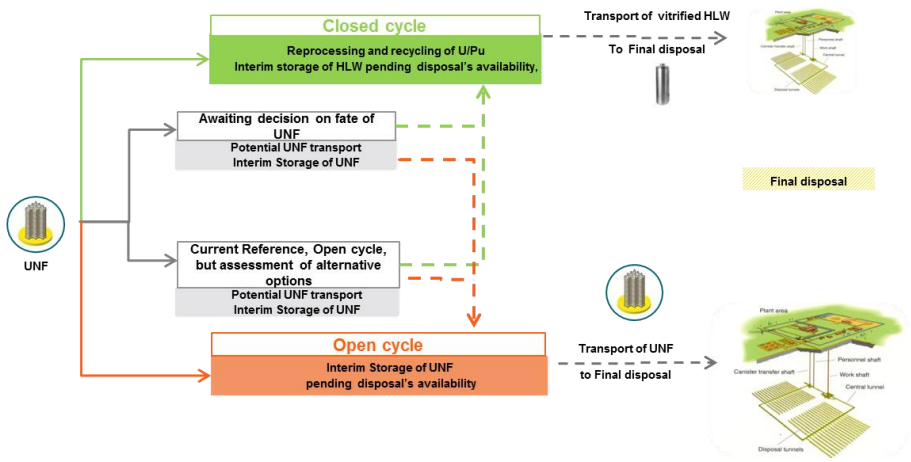


FIG. 1. Strategies for used fuel management.

Therefore, some key challenges arising to implement sustainable used fuel management programmes such as:

— Enhance Public acceptance and reduce the cost of geological repository
— Avoid reactor pool saturation and safely manage interim systems

Implementing disposal capacities of used nuclear fuel and or HLW involves extremely long planning horizon for siting a repository, construction, and emplacing the UNF or HLW. It remains a complex process, on the technical side (the safety demonstration in particular when fissile material is disposed emplaced in the geological repository) but moreover on the public acceptance and stakeholder involvement.

In addition, continued delays in making decisions for the development of a deep geological repository, transferring the burden to future generations increase both costs and the risk of failure.

Deep geological repository is dependent on the availability of suitable geological conditions in the country and will therefore:

— Remain a scarce resource: optimizing its use is therefore crucial for the durability of the nuclear energy
— Take more time to implement than expected: mastering the elapsed time to their full implementation is crucial to mitigate risks and uncertainties on any intermediate upstream steps in the management of used fuel.

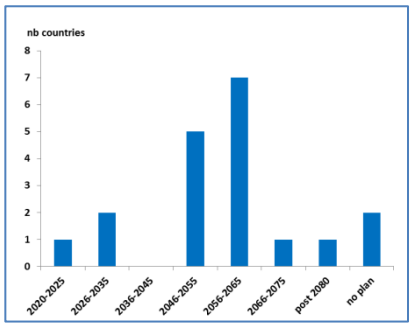


FIG. 2. Illustration of foreseen/forecasted DGR start of operation.

This situation has led to an interim storage over 250,000 tHM of used fuel worldwide; some of it has already been stored for over 60 years. Considering long time operation of the current fleet, there is a need to implement additional storage capacity, wet and dry, beyond those of the existing reactor pools in order to continue safe operation of NPPs. The used fuel inventory will continue to grow significantly in the next decades, taking into account both nuclear new builds and the increasing numbers of shutdown reactors.

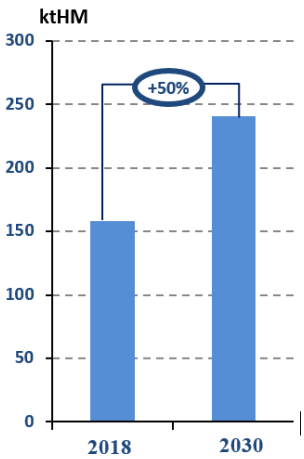


FIG. 3(a). Evaluation of LWR used fuel inventories.

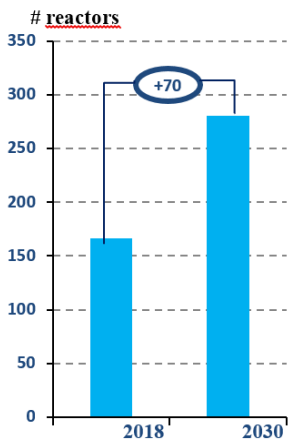


FIG. 3(b). Evaluation of shutdown reactors.

For all fuel cycles, as the requirements for storage capacity increase, new storage is being built outside of the reactor buildings. Different technologies, as illustrated in Figure 4, have been implemented or are planned, most of the capacities are using dry storage technologies on the reactor site, but some wet storage facilities are also being deployed.

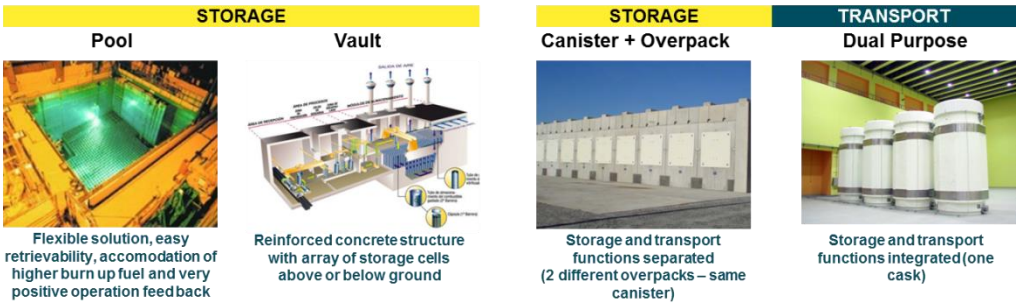


FIG. 4. UNF storage technologies.

The recycling strategies offer many benefits at different steps of the back-end of the fuel cycle starting from reactors' pools. Indeed for countries having chosen this strategy, used fuel are discharged from reactors' pools once cooled down and then transferred to dedicated facilities for recycling. With such a scheme, saturation of reactors' pool is therefore avoided, UNF storage capacity are significantly decreased. Over 100 000 tHM of used fuel has been reprocessed so far. The possibility to have reprocessing carried out abroad is an available strategy choice for any country with a nuclear power programme, since there is a commercial market providing reprocessing services.

For instance, since the mid 70's Orano La Hague reprocessing plants in France has reprocessed over 35,000tHM of LWR used fuel from nine countries of origins as per Fig 5. Reusable materials separated at the reprocessing stage have been recycled through MOX and ERU fuel loaded in LWRs. More than 2700tHM of MOX fuel have been manufactured at Orano Melox facility at the end of 2018. Ultimate High Level Waste are confined in glass matrix, using a high performance vitrification process which is key in the dispositive. So far 25000 universal vitrified canisters have been manufactured by La Hague.

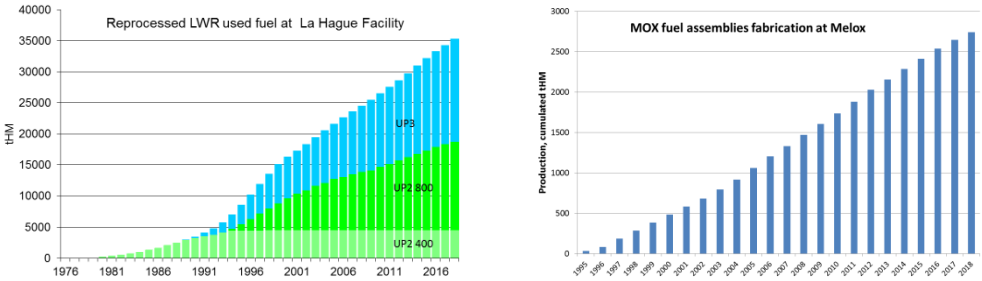


FIG. 5. Orano La Hague and Melox productions.

3. A VERY LONG TERM STRATEGIC MATTER WITH RISKS AND UNCERTAINTIES TO MITIGATE

3.1. Storage of UNF and subsequent transportation

All used fuel management schemes require storage of UNF, although the need is considerably alleviated when implementing a UNF reprocessing scheme. For example in France, storage capacities for over 45 000 fuel assemblies have been avoided.

For countries having chosen the open cycle or deferral of final decision strategy, long term (interim?) storage is today a reality. Historically, starting in the USA, used fuel assemblies have been stored on-site in dry storage systems designed for "bridging the gap" for the period of time needed before transportation to the DGR, intended to be for a period between 20 to 40 years. In many cases, there is a need to develop solutions to

manage storage facilities, most of the time scattered across many nuclear sites or in the near future stranded storage sites, for extended periods of time exceeding the original design or licensed reference.

The challenge is thus to ensure the long term safety and integrity of both storage system and the spent fuel for many decades to come:

— The SNF and its storage package will require aging management plans to monitor their conditions and include potential mitigation plans should degradation mechanisms occur. This need is already under development in the USA with requirements defined by the regulators and programme under implementation by industrial storage systems providers.
— The challenge goes beyond the storage facility itself. Eventually, the SNF will have to be transported from its initial storage location to a consolidated storage or a disposal facility. Transportation options and safety requirements may change over extended periods of time leading to having to recondition/repack UNF to ensure that the fuel in its future state is exported in packages suitable for transport.
— This may become even more challenging for "stranded sites" with no capabilities for handling fuel as reactor ponds have ceased operation. Indeed, options for detecting and mitigating potential problems during storage will change as fuel-handling capabilities are decommissioned at former reactor sites. Opening storage canisters at decommissioned sites for reasons such as repackaging fuel to replace damaged or degraded canisters or in response to future requirements on transportation may require building fuel-handling capabilities at the site.

Physical security requirements at storage sites will also change through time. Over longer periods, the dose rate at the surface of the canisters associated with the decaying radioactivity of the fuel decreases exponentially. With continued storage for many decades, stored UNF becomes more vulnerable, its self-protection through its own radiation decreases with time, its self-protection may not provide sufficient protection level against diversion, theft, or sabotage resulting in a need for increased security measures. Those measures will be required for decades, and for stranded sites, even after the nuclear power plant has been decommissioned.

3.2. UNF Encapsulation and DEEP GEOLOGICAL disposal

Encapsulation refers to the placement of the used fuel into robust engineered barriers designed to protect against leakage during long term disposal. Such facilities are even for the most advanced countries such as Sweden and Finland, still under design phase, with some challenges to overcome in terms of fuel characterization to serve both safeguarding requirements and optimization of heat load of final disposal canisters impacting the footprint of the GDF.

Some issues remain with safety demonstration of final disposal canister durability. A widely accepted principle for addressing the long term safety of radioactive waste and used fuel in a geological repository is that the isolation systems should be passive. However, used fuel emplaced in geological repositories is subject to safeguards, and obligation to implement safeguards remains after the repository's closure.

Reprocessing/recycling schemes provides engineered final waste with high confining performance, an additional barrier with demonstrated longevity of the waste integrity. Vitrified wastes have demonstrated capability for very long term safe interim storage and subsequent transportability. They can be stored in demonstrated, well-designed buildings, easily implementable for limited costs and that guarantee the needed radiation protection with passive surveillance only.

In addition taking out safeguarded materials from the waste allows significant reduction of final waste toxicity and volume. This leads to lower the footprint of the final repository, decrease the complexity of design and final waste emplacement operations and eliminates safeguarding requirements including those after repository closure. These features can benefit the global public acceptance necessary for the deep disposal implementation.

Management of used recycled fuel will differ with various recycling schemes, i.e. starting from a storage phase pending recycling or direct disposal. Monorecycling strategy is most of the time the first step towards implementation of a multirecycling strategy. Nevertheless, in case advanced cycles are not pursued, used Mox

and ERU used fuel will have to be disposed of in the GDF, leading to an anticipation ofadequate corresponding needs.

3.3. Used Fuel management programmes

The complete programme to implement responsible management of used nuclear fuel and safe disposal of nuclear waste will require a period of over a century. Looking at the main options, some steps are already industrialised, some are still to be deployed and this could extend considerably the overall duration of the programme. Thus this entails an evolution of risks and uncertainties over time which may be different for the two main management options. As illustrated in Fig 5, uncertainties of open cycle will increase significantly as interim storage of used fuel is extended pending final disposal availability. Recycling options, while dealing with used fuel will also have uncertainties associated with long term storage of final waste storage pending GDF availability, however those uncertainties are lower due to the intrinsic characteristic of this engineered waste form.

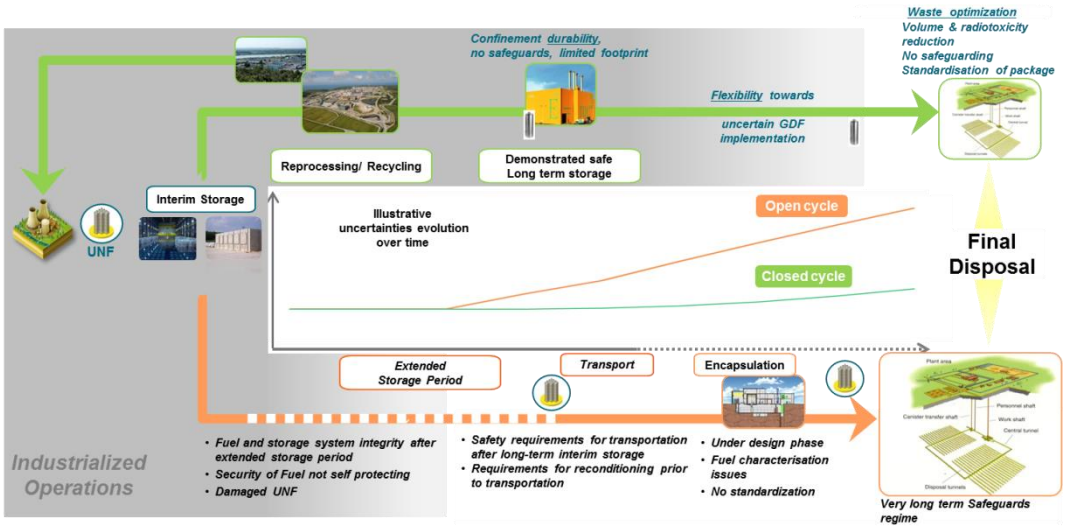


FIG. 5. Used nuclear fuel management: uncertainties evolution.

4. FOR UTILITIES AND GOVERNMENTS: HOW TO DECIDE IN AN UNCERTAIN FUTURE

Regardless of the selected cycle option, financial requirements have to cover all operations for the complete management of spent nuclear fuel up to the final disposal of radioactive waste, and even beyond the closure of geological disposal facility. It encompasses short-term implemented stages but also in a holistic approach the long-term ones, given the uncertainties including financial rate of return volatility (including current negative rate of return in some countries). Used fuel management programme should include clear plans for storage (on-site and centralized), transportation to reprocessing plant or final disposal facility, and emplacement of used fuel or HLW in a GDF. These activities are highly interdependent and require putting in place an integrated system approach.

Deferral of programmes and evolution of costs have different impacts on financial requirements depending on the actual nuclear programme status and its remaining time to operate, and the spent fuel management implementation status.

The initial stage, i.e. implementing interim storage, most of the time at reactor site, is often seen to require low financing resources. All of additional requirements for the downstream steps after long term interim storage mentioned previously will add to the costs of SNF management and will increase over extended periods of time.

In the long term, development of GDF and implementing of specific safeguards monitoring regimes will require significant financing with no defined end period.

Throughout the required programme, there are a limited set of strategic decisional points allowing choosing between alternatives. Influence can be made on when to trigger a decision milestone, for example, implementing dry storage systems at reactor site will lock decision on the corresponding inventory for a few decades. The decisional times, tdi as illustrated in Fig 6; are not continuums but should be decided upon such that maximal flexibility is provided in light of uncertain future developments in all of the UNF-management options.

The definition of UNF policy and corresponding program implementation will require addressing questions such as:

— At the UNF batch level, with analysis of cost/risk balance trade off with some specificities on certain fuel conditions (for example management of damaged fuel).
— Considering overall inventory of UNF exiting and still to come, analysis of the most affordable portfolio management and potential future issues looking at the most attractive alternatives, the time to trigger as well as conditions to execute those.
— Thus, finally being able to establish the program implementation strategy and securing a critical path for implementing an optimized used fuel management solution and guide development efforts to reduce uncertainties/risks (when is the best moment to contract an option in terms of capacity and duration).

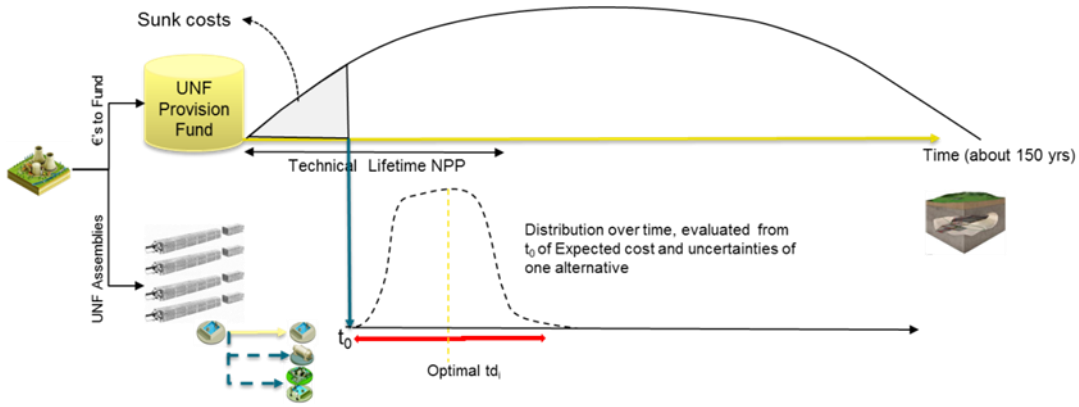


FIG. 6. Illustration of decisional time over the overall used fuel management programme.

For historical utilities with short remaining lifetime of reactor operation, uncertainties associated to used fuel management leads to potential significant increase of required provisions or fees to cover used nuclear fuel inventories management. These situations may translate in significant financial risks and therefore trigger decisions from utilities or stakeholders to mitigate exposure when revenues from operation are limited or have even ceased.

5. DIFFERENT RISK /COST EXPOSURE OVER TIME WITH DIFFERENT FUEL CYCLE OPTIONS

Various fuel cycle options have different cost profiles but also different risks and uncertainties evolving over time: open cycle showing low short-term requirements but uncertainties increasing with time, close cycle options having higher short or mid-term requirements allowing securing long-term operation, thus reducing future uncertainties. Considering open cycle and more specifically dry storage at reactor site, although the significant financial requirements may seem to be far away, risks and uncertainties associated to the very long-term planning increase significantly with time as shown in Figure 7. Indeed, critical stages of transport, conditioning in final disposal canister and disposal operations could require additional unplanned financial means corresponding to an evolution of security and safety requirements, ageing management programmes of storage systems, repacking requirements prior to transport, consolidated storage awaiting final geological repository siting, future significant use of potential scarce resources such as copper…

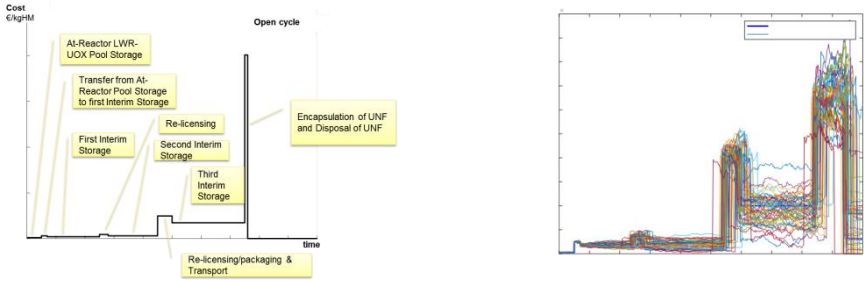


FIG. 7. Nominal Expected Cost-Curve over time and uncertainties applied cost curve for open cycle.

When evaluating /revaluating the program implementation strategy at a decisional point, the value of various available alternatives including pursuing open cycle or wait and see, but also switching from interim storage towards recycling will be assessed over time considering the combination of costs and risks.

Illustrated in Figure 8 is an example considering the comparison between open cycle (dry interim storage) and mono-recycling.

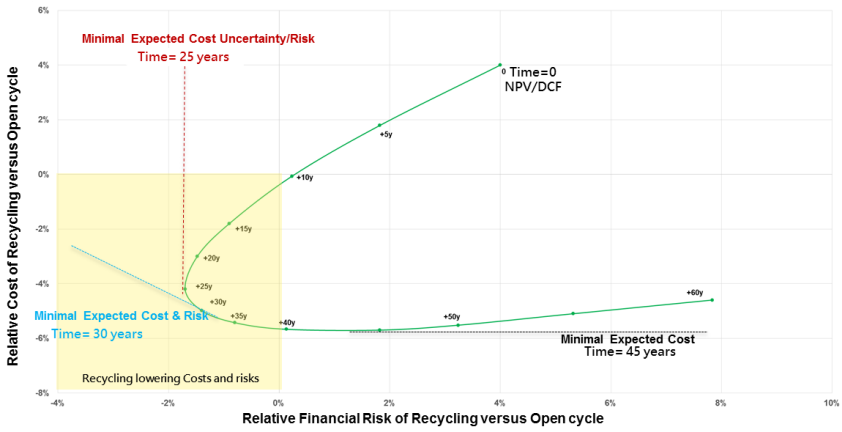


FIG. 8. Illustration of relative cost/risks of alternatives including mono-recycling versus open cycle over time.

The analysis integrates a wide range of assumptions and or assessments such as expected cost of each step of the compared two options, associated uncertainties both in time and cost and financial assessments (discount rates, financial rate of return...). It needs to be customised to each specific situation.

Such analysis allows the evaluation, as seen from today (time t0), of expected cost and uncertainties for the existing and forecasted UNF inventory comparing different fuel cycle options and switching moments in time.

At t0 the comparison naturally corresponds to the NPV/DCF method. When projecting switching at later decisional times, tdi, the cost of the two alternatives are similar then differing from this point onwards:

the recycling option will limit exposition to known and unknown consequences of long term dry interim storage at the reactor site.

Indeed reprocessing leads to less amounts of used UOX to be exposed to increasing uncertain requirements from extended interim storage and downstream steps up to GDF costs while providing an option with higher cost predictability. Thus, switches from 10 y from today, up to 40y, lowers the total cost as viewed from today (including discounting) compared to carrying on with the open cycle implementation.

However, waiting longer may further expose to interim costs and GDF costs uncertainties of used fuels. Thus the exposition to the consequences of interim storage will be more important compared to those at an earlier decision switching point (this is due to Pu quality decrease impacting reuse performance and Used MOX fuel disposal assuming an define opening window for the GDF)

6. HAVING FLEXIBILITY IN THE BACK END OPTIONS OFFERS MITIGATION TO KNOWN/UNKNOWN RISKS

Used fuel and related waste management requires an overall long-term multi-dimensional system approach however implemented in stages. A suite of options could be available in time. Pending future informed decisions a safe, economic, mitigating risks and uncertainties solution can be deployed. Used fuel management system involves multiple decisions over time encompassing conflicts of drivers, uncertain factors and alternatives arising as the market conditions evolve.

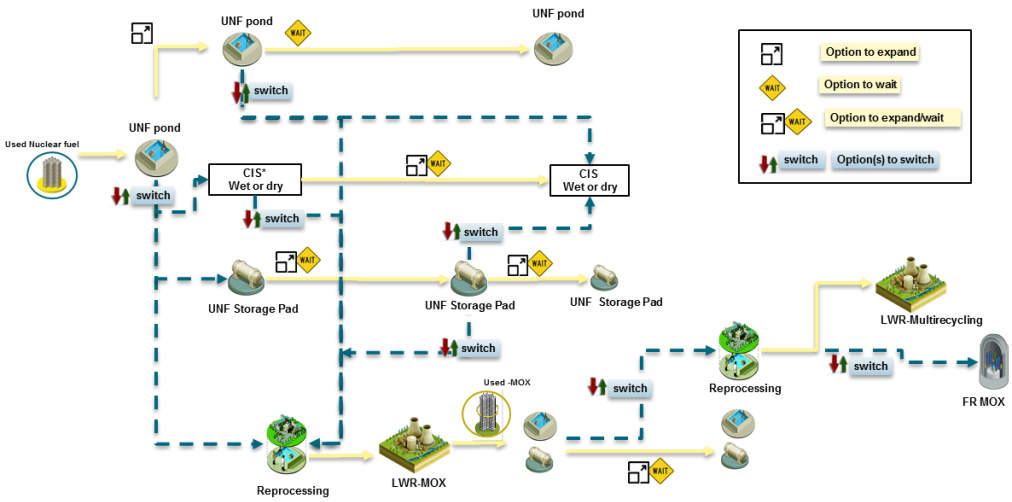
Uncertainty and risks are of different natures. Some are technical- economic such as evolution of commercial service cost or investment overruns, maturity of technology encapsulation and disposal facility and consequences of extended storage of UNF. The evolution of natural uranium market price is also a factor, directly affecting the competitiveness of GenIV technology and as such the horizon of its commercial deployment which is not currently foreseen until the second part of this century. Beyond environmental, socio-political (evolution of installed nuclear capacities, security and safety requirements, social acceptance of UNF management options,), and financial (discount rates, financial rate of return and utilities competitiveness) aspects will also play significant roles in the optimum route to implement.

International R&D cooperation is undergoing on advanced cycle and reactor technologies and for GDF developments. The nuclear industry is also continuously developing services and solutions to provide additional alternatives to nuclear reactor operators and their stakeholders. Typically Orano's focus is to improve our reprocessing /recycling services to enhance our scope of services and enlarge our capacities/capabilities based on the lessons learned from our extensive industrial experience and driven by both R&D and innovation efforts. This leads to extend our capabilities to reprocess various types of UNF including VVER fuels from HBU fuels, damaged fuels. Concerning recycled fuel and more specifically MOX fuels, efforts are pursued both on the fabrication process improvement and on fuel developments to increase current MOX fuel performances, and develop MIX and Corail concepts allowing to multi-recycle Pu in LWR, thus bridging the gap with the future development of GEN IV reactors. This allows offering a wide range of alternatives using existing shared industrial reprocessing/recycling capacities to various countries. Additionally collaborations with various countries to develop their indigenous reprocessing-recycling capacities are ongoing. To manage at best the potential risks of long term interim storage, new storage systems such as NUHOMS EOS or MATRIX encompassing ageing management requirements by design, reduced footprints or consolidate interim storage infrastructures under development will allow shifting the interim storage step paradigm from a "commodity" to "critical interim system".

The back-end of the fuel cycle presents various options branching into a multitude of scenarios Therefore, flexibility in back-end options offers mitigation for known/unknown uncertainties and risks.

All these industrial developments provide flexibility in the used fuel management program allowing minimizing risks and containing costs thus enhancing overall financial predictability of the comprehensive used fuel management solution.

There is no fixed scenario as alternatives arise with new development and the evolution of market conditions. Each decisional branching point involves a value to wait, to extend (in capacity or in duration, for example relicensing of dry storage systems), or to switch options as per Fig 9.



**CIS: consolidated Interim Storage*

FIG. 9. Illustration of alternatives to manage used fuel.

The future value of an option is also depending on the developments made to keep the option open, i.e. the value to lose or gain if you do not have the option anymore available.

Using an innovative assessment methodology such as Real Alternative Valuation integrating costs, risks, time and options to determine optimal fuel cycle option can guide utilities and their stakeholders to decide which option to develop and when, thus allowing to secure implementation of a future risk-mitigating strategy.

Multi-capability industrial service approach, developed by nuclear fuel cycle operators such as Orano will allow to implement a customised used fuel management programme matching each NPP-operator's and stakeholders specific context and financial cost/risk objectives in dynamic and uncertain market environments.

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