**THE RESPONSIBLE MANAGEMENT OF USED FUEL**

**BY THE NUCLEAR INDUSTRY**

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**Abstract**

Used fuel is generated from the operation of nuclear reactors of all types. The nuclear industry is currently implementing strategies to ensure the safe and cost-effective management of this used fuel. Currently, there exist two strategies for managing used fuel: the “open cycle” and “closed cycle”. Depending on a number of drivers, countries will engage in one of these alternatives, but may also examine the use of interim storage.

The paper presents used fuel management strategies which ensure used fuel is safely managed by the nuclear operators. The paper also discusses long-term management solutions of used fuel, implementing integrated system approaches in stages to mitigate risks and uncertainties. Additionally, described are innovative solutions that could be implemented in the mid-term, as well as potential constraints to their development.

1. INTRODUCTION

The central apparatus of any nuclear power plant (NPP) is the reactor core. A fuel assembly enjoys a working period of three to six years within the reactor core and is used in all types of nuclear reactor designs[[1]](#footnote-1). Upon removal from the reactor core, this used fuel embarks on the final stage of its life cycle, with the nuclear industry implementing various strategies based on government policy to ensure a safe and cost-effective overall management of this used fuel, which is divided into two tracks: the “open cycle” and the “closed cycle”. Due to a number of factors (e.g., State policy, technology availability, geology, public acceptance) nuclear operators may avail themselves of interim storage methods. Whichever method is chosen, the infrastructure and technologies are available for meeting the current and future used fuel management needs of these countries, until such time a deep geological repository (DGR) becomes operational.

The main objectives of the World Nuclear Association’s Sustainable Used Fuel Management Working Group (SUFM) are to share and promote sound, safe, sustainable and proliferation-proof used fuel management and explain how used fuel management can further contribute to the sustainability of nuclear energy. In line with these objectives, the paper presents existing and emerging industrial infrastructures safeguarding used fuel management activities for whichever track is available to nuclear operators. The paper also discusses long-term management solutions of used fuel, implementing integrated system approaches in stages to mitigate risks and uncertainties. Additionally, described are innovative solutions that could be implemented in the mid-term, as well as potential constraints to their development.

1. THE SUFM APROACH TO USED FUEL MANAGEMENT

SUFM is a working group of dedicated individuals spanning the globe and who work within numerous aspects of the nuclear apparatus, notably in industry. Its members strive to promote the sound, safe, sustainable and proliferation-proof management of used fuel through the sharing of information and best practices. It accomplishes this through the gathering of the views and insights of the nuclear industry and stakeholders (including newcomers) on the back-end of the fuel cycle and considers how the industry can best respond to the concerns and needs of its members. SUFM helps to explain how used fuel management can further contribute to the sustainability of nuclear energy through information gathering activities and participation in preparing reports and papers. Finally, SUFM produces guidelines or objectives to aid communicators (i.e., utilities, media, communication agencies, politicians and other stakeholders) to more effectively communicate with the public.

For nuclear power to be a compelling method of energy production, and to gain a better public perception, used fuel management must be seen as “sustainable”. SUFM has developed the pertinent conditions it believes are necessary for achieving this sought-out sustainability. SUFM’s approach for achieving the sustainable management of used fuel is presented in Figure 1.



Fig 1: SUFM Approach for Achieving Sustainable Used Fuel Management

1. CURRENT AND PROJECTED FUTURE INVENTORY OF USED FUEL

Current and future projected inventories of used fuel are generally presented in metric tonnes of heavy metal (tHM). The approach is useful as it describes the mass of heavy metals (e.g. plutonium, thorium, uranium and minor actinides) contained in the used fuel. From the start of nuclear power-based electricity production in 1954, though to the end of 2016, a total of about 390 000 tHM of used fuel has accumulated from all nuclear power plants worldwide[[2]](#footnote-2), with ~ 30% of this used fuel being reprocessed. Over half of used fuel is kept in wet storage at site in spent fuel pools (SFP). After an initial cooling period of at least a few years in a SFP, some used fuel has been transferred into site specific/centralized dry storage or wet storage facilities. Figure 2 shows the share of this fuel for the different types of storage[[3]](#footnote-3) [1].



Fig 2: Nuclear Power Plant Spent Fuel Storage by Type

It is expected that the used fuel inventory from nuclear power reactors will, however, double between 2015 through to year 2040. When considering the present trend in power plant decommissioning coupled with current envisaged new build projects, this used fuel inventory is expected to reach almost 600,000 tHM by 2050, with a substantial share of this growth occurring in Asia.

1. PRESENT AND FUTURE MANAGEMENT OF USED FUEL

Used fuel that is discharged from power plants is successfully managed according to existing and mature infrastructures and technologies, while also protecting human health and the environment. This is a fact associated with either chosen route of used fuel management a nation undertakes currently, or whichever route (or routes) these States embark on in the future. The planned disposition of used fuel is summarized in Figure 3 based on the fraction of the total tHM of used fuel that has been discharged to date.



Fig 3: Summary of Existing Spent Fuel by Planned Disposition.

Currently, there exist two strategies to ensure a safe and cost-effective overall management of used fuel. As previously discussed, the chosen strategy differs from one country to another. The *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Management* [2] recognizes the importance of fuel cycle policy remaining the prerogative of the State[[4]](#footnote-4) to make according to its goals, which is described in Table 1.

**Table 1: The Two Strategies for Used Fuel Management**

|  |  |
| --- | --- |
| **Option**  | **Description**  |
| **Open Cycle** | Referred to as the “once through” strategy. It considers spent fuel as a waste product. Following a period of interim storage, the spent fuel is packaged to meet disposal acceptance criteria before final disposal in a DGR. |
| **Closed Cycle** | This strategy considers spent fuel to be a potential future energy resource, and also includes the “partially closed cycle”. The spent fuel is reprocessed in order to recover valuable fissile materials (uranium and plutonium). The High-level waste (HLW) (along with other wastes such as Low-level (LLW) and Intermediate-level (ILW) waste resulting from reprocessing is then stored awaiting future disposal, normally in a deep geological repository. It should be mentioned that the “closed cycle” can refer to one or more cycles of the recovered valuable material. |
| Alternative Option |
| **Alternative****Method** | States may seek flexibility, while keeping open the option to examine ‘other’ alternatives. A number of countries are awaiting a decision on the future strategy to be implemented or consider the open cycle as its current reference.  |

The majority of countries have adopted or reference the “open cycle” strategy, while certain countries with some of the largest nuclear power programmes (e.g. France, United Kingdom, Russian Federation, Japan and China) have adopted a “closed cycle” policy. Other countries with a small nuclear fleet, like the Netherlands, have also opted for the closed cycle strategy, with reprocessing services provided by commercial companies in another State having this capability. Additionally, there are other countries, namely Germany, United Kingdom[[5]](#footnote-5) (UK) and the United States of America, that have changed their policy from a “closed cycle” to “open cycle”.

It should be noted that the amount of used fuel from non-power reactors is not dealt with within the confines of this paper. However, it is interesting to note that some countries are returning their non-power reactor used fuel to the country of origin, mainly the Russian Federation and the United States of America (USA), while others , such as Australia[[6]](#footnote-6), Belgium[[7]](#footnote-7) and Sweden[[8]](#footnote-8), have opted to reprocess this spent fuel from their research reactors.

* 1. **The “Closed Cycle”: Reprocessing of Used Fuel and Reuse of Uranium and Plutonium**

Used fuel undergoing reprocessing is separated into several main components: uranium, plutonium, and waste containing minor actinides, fission and activation products. The uranium and plutonium can be recycled as part of nuclear fuel for reactors, while the minor actinides, fission and activation products are currently considered to be waste products. The minor actinide and fission product wastes are vitrified, followed by its interim storage in a very stable matrix before its transport and final disposal. The main activation products (hulls and end-pieces) from reprocessing are conditioned in a stable matrix and also interim stored awaiting final disposal.

Currently, the countries which operate reprocessing facilities are France, India, and the Russian Federation. The UK previously operated reprocessing facilities for Light Water Reactor fuel until recently (closed in 2018) and will still operate the Magnox reprocessing plant until around 2020[[9]](#footnote-9). China is operating a pilot plant and is looking to deploy demonstration and industrial facilities. Japan is planning to commission in 2021 its Rokkasho-Mura plant, including implementation of safety measures required following the Fukushima accident[[10]](#footnote-10). In the past, reprocessing was also carried out by the USA. India[[11]](#footnote-11) has and is developing reprocessing facilities for both thermal and fast reactor spent fuel. Additionally, it has developed a unique strategy for using its Thorium reserves in its advanced reactors, after breeding U233 in fast reactors. Other countries[[12]](#footnote-12) have used services provided by foreign facilities (e.g., UK, France and the Russian Federation[[13]](#footnote-13)) for the reprocessing of their fuel.

The commercial capacity for reprocessing of used fuel was 4,800 tHM in February 2018. This capacity will experience a temporary reduction phase, before enjoying an upswing as new facilities in the Russian Federation, China and Japan come into operation.

**4.2 The “Open Cycle”: Direct Disposal of Used Fuel**

The “open cycle” option[[14]](#footnote-14) views the used fuel as waste. Used fuel may initially be stored for several decades to allow the decay heat to be reduced, though this timeframe is likely to increase depending on the progression of a DGR in the State. Before being sent to the DGR for final disposal, the used fuel is to be encapsulated in a corrosion resistant and mechanically stable container, which will provide isolation for a suitable duration (often thousands of years or more). The requirements for the container life and integrity depends on the DGR concept and the chosen geological medium. Depending on the adopted disposal concept, an extra container or overpack for the used fuel container may be required.

There is presently a broad consensus among technical experts that the preferred method of ensuring long-term safety for HLW and used fuel is isolation in a DGR. Geological disposal facilities for long-lived waste, if properly sited and constructed, will provide passive multi-barrier isolation of radioactive materials. Investigations are ongoing for different types of geological media and associated engineered barriers in many countries. Emplacement in carefully engineered structures buried deep within suitable geological formations provides for the long-term stability of used fuel management. At depths of several hundreds of metres, in a tectonically stable location, processes that could disrupt the disposal facility are so slow that the deep geological layers and groundwater system remain practically unchanged over hundreds of thousands or even millions of years.

* 1. **Drivers for Used Fuel Management Strategies**

Countries choosing the “open cycle” generally have no immediate interest or purpose in using the uranium and plutonium recovered from the reprocessing of the used fuel. From a financing point of view, the “open cycle” allows the nuclear operators to finance interim storage costs early on, which are relatively low and supports at a later stage the future costs of the encapsulation facility. Moreover, this allows flexibility by the nuclear operator to decide in the future whether to continue with an “open cycle” or to switch to the “closed cycle” route. This will require both an initial interim storage facility and later construction of an encapsulating facility before the used fuel is eventually disposed in a DGR. This latter stage could occur many decades after the used fuel has been discharged from the reactor.

Other countries make the choice of the “closed cycle”. Generally speaking, the recycling activities are considered to be a sustainable approach and are usually promoted at the national level. Recycling in the nuclear industry is in line with this principle by taking advantage of the valuable material contained in the used fuel in view of its reuse in recycled fuel. Consequently, reprocessing allows further reduction of the radiotoxicity and volume of the HLW to be disposed in the DGR, together with the conditioning in the best available matrix. Moreover, it allows for standardization of HLW packages and provides a savings up to 15 to 25% of natural uranium resources. More decisively for these countries, it keeps the recovered uranium and plutonium available not only for the Gen III reactors, but also for Gen IV reactor deployment.

The strategy at the national or corporate level plays indeed a dominant role. Some countries may decide to prepare the ground for the future development of nuclear energy through the deployment of the Gen IV nuclear power plants, increase/secure their independence towards the uranium supply, or ensure other flexibilities by keeping all options open. Some countries with a small nuclear power plant fleet may want to define an overall implementation plan while maintaining the option of a possible future shared solution for their used fuel management. These drivers forming the Sustainability Model are presented in Table 2. Looking at the driver, Economics, the most recent study comparing the competitiveness of “open” and “closed” cycle concludes that these two approaches are economically comparable when fully integrating the total fuel cycle costs [3].

**Table 2: The Drivers of Sustainable Used Fuel Management**

| **Driver** | **Description** |
| --- | --- |
| **Economics** | Concerns the economic viability for the nuclear fuel cycle, including the funding and building a DGR. This compartment plays a central role in policy decisions. For example, the “closed cycle” allows for the reuse of valuable material which generates fresh uranium savings, while the “open cycle” reduces the cash flow curve for the nuclear operator postponing at a later stage the financing for an encapsulation facility. It also provides the nuclear operators the flexibility to decide the used fuel management option that could be chosen. Moreover, socio-economic development opportunities may be considered of importance through the industrial infrastructure that one option or the other may generate. The medical use of radioisotopes recovered during reprocessing operations may also impact the overall economy considered. |
| **Environment** | The driver ensures that environmental factors are at the forefront of decision-making processes throughout the nuclear fuel cycle in minimizing as far as possible any negative effects on all stakeholders, and that these are thoroughly investigated and taken into consideration. For waste disposal, the packages to be disposed of in the DGR are encapsulated used fuel in the “open cycle” route. The encapsulated used fuel package still contains major actinides (uranium and plutonium). In the case of the “closed cycle” route, these actinides are separated from the fission products reducing thus the radiotoxicity of the HLW to be disposed of in the DGR. In addition, the lower overall volume of the HLW allows for a smaller footprint of a factor 3 to 4 of the DGR. |
| **Society/Politics** | Ensures that ample oversight is given to the waste management facility siting, design, construction and operation so that these activities reflect the desires and will of the society. Further ensures that dedicated decisions taken at the national level, such as the compliance with a law or a directive, the need to integrate the public or social acceptance in decision-making processes, or the deployment of industrial vision taken at the national level is kept in focus.  |
| **Non-proliferation** | Such considerations vary from the “closed cycle” to the “open cycle”. In the latter case, the valuable material is contained in the used fuel to be disposed, thus creating a need for a safeguards control regime during a period to be determined to provide for its security and physical protection. In the case of the “closed cycle” route, HLW to be disposed are free from any safeguards control regime. The separated plutonium having been separated with the objective to be recycled would, however, need to be managed under a safeguards control regime.  |

It is important to point out that a used fuel management strategy is always defined at the national level, even though it is the nuclear operators as privately-owned companies that must make certain strategic decisions within this framework. It should be observed that the main factor leading to the choice of a used fuel management strategy in the frame of a long-term vision of an overall national energy program is usually driven primarily by the compartment of Politics, pushed along by social factors inherent to the State. Moreover, while important, the economical factor is not considered as the primary driver in decision-making processes. Additionally, keeping flexibility for later options is also an important piece of the decision-making puzzle. This approach could be of interest to the new comers to the nuclear industry as a driver for the definition of their strategy. Autonomy, or controlling one’s own destiny, is also another major factor influencing the option chosen.

In general, it appears that most countries with a large nuclear program have independently implemented their used fuel management strategy with a long-term view. With the exception of the USA, the other major nuclear countries have made the choice of the “closed cycle” with the long-term view of the implementation of Gen IV reactors. Delays in such implementation could occur and may raise some concerns related to the management of the valuable materials if not recycled in the Gen III reactor fleet.

* 1. **Challenges and Achievements**

Section 4.1 presents ongoing used fuel management opportunities and demonstrates that all parts of the back-end of the fuel cycle (interim storage, recycling, and transportation) are industrially and safely implemented presently and for the next decades, whatever the delay in constructing a DGR facility. In fact, clear progress is being made in three countries (Finland, Sweden and France) with defined schedules. It should be recognized that carrying out the construction and operation of a DGR is and continues to remain slow in many countries for the foreseeable future. This has resulted in the need for planned or continuing interim storage (planned, built and operated as AR or AFR sites) for used fuel and HLW until DGRs are available. However, the progress at the back-end of the nuclear fuel cycle does face a number of potential challenges, as presented in Table 3.

**Table 3: Potential Challenges Facing Used Fuel Management Activities**

|  **Challenge**  | **Description**  |
| --- | --- |
| **Challenge 1**(Interim Storage) | The length involved in the interim storage of used fuel will expand over many decades. As the requirements for storage capacity for used fuel are increasing, new storage is successively being built outside of the reactor buildings (AR or AFR). Most of these facilities are dry storage, but some wet storages pools are also being built. The challenge is to ensure the continued safety of existing systems and to design new systems with an extended storage period that allow for suitable ageing management.  |
| **Challenge 2**(Transportation) |  Used fuel will have to be transported, possibly after repackaging when required in the frame of the “open cycle”, and then possibly transported again to the DGR. A significant challenge is related to handling of the used fuel and its integrity after several decades of storage following an extended period of interim storage, especially in dry storage conditions. |
| **Challenge 3**(Public Perception) | There are a number of challenges surrounding the public perception of nuclear power programs, including long-term storage of used fuel, following (i.e., Fukushima and Chernobyl), as well as the NIMBY (Not In My Back Yard) syndrome with any associated public misinformation. |
| Once a site has been chosen and accepted by the public, maintaining public acceptance over the duration of the project will also be a challenge, since this process will extend many decades to a century or more in some cases. Causes leading to delay in the schedule for a DGR include: (1) Identification of the siting activities; (2) Fluid public acceptance; (3) Technical implementation; and, (4) Regulatory lack of experience in licensing such facilities. |
| **Challenge 4**(Siting Approach) | Most countries are facing delays in their programmes for the DGR of used fuel and other HLW. In certain cases, the process to find a site has completely restarted, with some countries taking a science focused siting approach. Still, other countries are committed to a consent-based model. Additionally, there are States that are embarking on a hybrid siting approach, which is a combination of science/consent-based siting.  |

1. AN INDUSTRIAL VIEW OF THE R&D AND INNOVATION IN USED FUEL MANAGEMENT

Today, in the more liberalized and competitive energy market the focus on used fuel management leans towards the reduction of costs given the uncertain risks of the future unknown aspects of used fuel management activities. There have been essentially three “waves” since the initial developed practices with used fuel management, which are presented in Table 4.

**Table 4: Historic Trends in Used Fuel Management**

| **Trend** | **Development** |
| --- | --- |
| **Wave 1** | Wave 1 dates back to the first decades of nuclear energy development where the transition towards fast spectrum reactors and closed fuel cycles was largely motivated by the reduced dependency on natural uranium, while also reducing the amount of spent fuel to be managed. |
| **Wave 2** | The second wave covers the continued delay in DGR deployment programs. This includes State government, as well as international initiatives, studying options to reduce the amount and radiotoxicity of the waste to be disposed of. The Partitioning and Transmutation research seeking the most advanced fuel cycle options aimed at maximally reducing the amount of waste and transuranic content of the wastes is also associated with wave 2.  |
| **Wave 3** | Wave 3 operates nearly in tandem with wave 2, as the nuclear industry and utilities deploy new and innovative approaches to further the performance of fuels and the waste arising from Nuclear Power Plants and fuel cycle facilities. These performance gains guarantee continued competitiveness and compliance with regulatory changes over time. |

While the strategic objectives of the first two “waves” may continue to remain relevant in the long run, utilities will need to ensure that short to long-term management of used fuel is adequately manages long-term risk, while being exposed to an increasing amount of uncertain socio-political and technical-economic impacts increasingly affecting their competitiveness and financial rating.

Today’s solutions, fruit of past Research & Development (R&D) provide a number of avenues for improved sustainability of used fuel management activities. In this regard, new build projects and fuel cycle developments may see industrial deployment during the coming two decades as an outgrowth of today’s investments and R&D. Particularly, multi-recycling schemes in LWR[[15]](#footnote-15)/VVERs[[16]](#footnote-16) could provide solutions to used fuel management in meaningfully reducing their cost and risk exposure. Choices in tomorrow’s R&D will lead to further improvements though, the fruits of these efforts will not be realized until the latter half of this century. Fortunately, there is no shortage of evolutionary and innovative solutions to further improve used fuel management, as shown in Figure 4.



Fig 4: Overview of Synergistic Options for Improved Used Fuel Management

1. CONCLUSIONS

As presented herein, industrial infrastructures and technologies are readily available (or planned) to assist in the efficient and safe management through the various stages of the used fuel cycle (i.e., storage (wet or dry) (AR or AFR), reprocessing, recycling and transportation (road, rail, sea)). With regard to choosing an “open” or “closed” fuel cycle, despite ongoing delays in siting, constructing and operating a DGR, this does not impose an inordinate discriminatory economic impact when comparing the “open” and “closed” cycle. However, this is not the case with other aspects of used fuel management. Indeed, in the case of the “open cycle”, the long-term storage of used fuel may raise specific issues in terms of safety (cladding integrity) or security (physical protection), while the long-term storage of reprocessed spent fuel and other HLW does not raise such additional issues.

Proposed timelines for the operations of DGRs varies from country to country but to-date it is estimated that the earliest operation of a DGR may occur in 2024, with other successive operational start-ups occurring throughout the 21st Century. Most designs for used fuel and HLW disposal are strongly influenced by the heat load of the waste. A reduction in heat load would make the design of a DGR more compact and, in some respects, easier to design. A positive side effect of current delays in implementing the DGR is that it reduces the radioactivity and subsequently the heat load that will be emplaced in the DGR. However, it causes upper ground interim storage to be seen as indefinite ‘interim’ storage with no end-point, triggering stronger negative views from the public and politicians on issues surrounding nuclear waste management.

Finally, currently available and/or planned infrastructures will provide for the safe and secure management of used nuclear fuel and other HLW for many decades, while efforts to complete and operate a DGR continue. Though there are a few positive trajectories in three countries (i.e., Finland, Sweden and France) it is likely imagined that most of the planned DGR projects will suffer some type of lengthy delay, mostly as a result of lack of political ambition, influenced by negative social views of long-term disposal of nuclear waste. This being said, the global nuclear industry has full capacity to mitigate both seen and unseen risks or uncertainties, all while it continues to develop implementable innovative programs to constantly increase efficiency and safety.

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1. See International Atomic Energy Agency, “The Nuclear Fuel Cycle”, <https://www.iaea.org/sites/default/files/nfc0811.pdf>, viewed June 04, 2019. [↑](#footnote-ref-1)
2. This includes used fuel discharged in India and Pakistan. [↑](#footnote-ref-2)
3. In Figure 2, “AFR” is away-from-reactor and “AR” is at-reactor. [↑](#footnote-ref-3)
4. See: Preamble para. vii [↑](#footnote-ref-4)
5. The UK has opted for an “open cycle” strategy for Sizewell B and the 16GWe of New Build to be implemented. All existing commercial scale reprocessing in the UK has already been terminated or will be terminated in the near future. [↑](#footnote-ref-5)
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12. This includes: Belgium, Bulgaria, Hungary, Ukraine, Czech Republic, Germany, Italy, Japan, the Netherlands, Slovakia, Spain, Sweden and Switzerland. [↑](#footnote-ref-12)
13. Including the time period of the former Union of Soviet Socialist Republics. [↑](#footnote-ref-13)
14. Also known as “once through” or “direct disposal” cycle. [↑](#footnote-ref-14)
15. See: Hesketh, K., A REVIEW OF MULTIPLE RECYCLE OF PLUTONIUM IN LWRS, <https://inis.iaea.org/collection/NCLCollectionStore/_Public/28/047/28047174.pdf?r=1&r=1>, Accessed May 23, 2019. Also see, Nuclear Energy Agency, Working Party on Scientific Issues of Reactor Systems (WPRS), “Physics of Plutonium Recycling”, <https://www.oecd-nea.org/science/wprs/wppr/execsum.html>, Accessed May 2, 2019. [↑](#footnote-ref-15)
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