THE RESPONSIBLE MANAGEMENT OF THE USED NUCLEAR 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 ensuring a safe and cost effective overall management of these used fuel. The strategies considered are the open cycle and the closed cycle. Besides these strategies, some countries may decide to consider the open cycle but, depending on a number of drivers (such as country policy, technology availability, geology, public acceptance, present and future nuclear program, …) may also examine alternative options. The used fuel is in that case interim stored. The paper aims at presenting the existing and under development industrial infrastructures for used fuel management which ensure that whatever the options the used fuel is safely managed by the nuclear operators. On the long-term, integrated system approaches are implemented in stages to mitigate risks and uncertainties. Moreover, the paper describes as well the innovative solutions which could be implemented in the mid-term and the constraints to their development. Lessons learnt from the successful used fuel management from research reactors that could be applicable to nuclear power reactors are also presented. The Sustainable Used Fuel Management Working Group of WNA main objectives are to share and promote sound, safe, sustainable and proliferation-proof used fuel management and explain how used fuel management could further contribute to the sustainability of nuclear energy.

1. INTRODUCTION

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The paper aims at presenting the existing and under development industrial infrastructures for used fuel management which ensure that whatever the options the used fuel is safely managed by the nuclear operators.

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2. THE WNA APPROACH IN TERMS OF SPENT FUEL MANAGEMENT

Since many years, the WNA has set a dedicated Working Group which main objectives are to:

- Share and promote sound, safe, sustainable and proliferation-proof used fuel management;
- Gather the views of the nuclear industry and stakeholders (including newcomers) on the back-end of the fuel cycle and to consider how the industry can best respond to these needs;
- Explain how used fuel management could further contribute to the sustainability of nuclear energy;
- Produce guidelines or objectives for communicators (utilities, media, communication agencies, politicians and other stakeholders) to use to in communication with the public.

The WNA has defined the conditions to which spent fuel management has to fulfill to be recognized as “Sustainable”.

These conditions are the following:

- It covers all steps of spent fuel management from generation up to and including final disposal (in accordance with well-defined practical plan);
- It includes realistic financing plan;
- It is able to demonstrate to a practicable extent that it is technically and economically viable;
- It answers to present needs while also protecting human health & environment;
- It has no greater impact on health of future generations than is allowed today.

3. WHAT IS THE CURRENT AND FUTURE INVENTORY OF SPENT FUEL

The amount of spent fuel is generally presented in metric tonnes of heavy metal (t HM) and describes the mass of heavy metals (e.g. plutonium, thorium, uranium and minor actinides) contained in the spent fuel. Since the start of nuclear power-based electricity production in 1954 to the end of 2016, a total of about 390 000 t HM of spent fuel was discharged from all nuclear power plants worldwide (the spent fuel discharged in India and Pakistan are reported). More than 30% of this amount has been reprocessed, while the majority (around half) is held at nuclear power plant sites in wet storage in the reactor pools. After initial storage for cooling for at least a few years in the reactor pool, some spent fuel has been transferred to dry storage or to centralized wet storage facilities. Figure 1 shows the share of this fuel for the different types of storage. (Ref IAEA Energy Technical Series NW-T-1.14 Status & Trends on spent fuel and radioactive waste management).

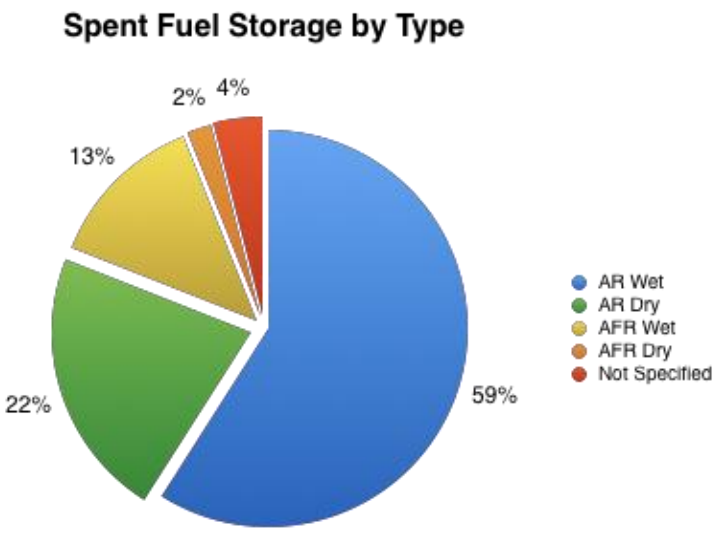

FIG. 1. Nuclear power plant spent fuel storage by type (AFR — away-from-reactor; AR — at-reactor).

Considering the present trend in power plants shut down and new build, the spent fuel inventory is expected to reach almost 600.000 tHM by 2050 with a substantially share of the growth in Asia.double by Spent fuel inventory from nuclear power reactors will double from 2015 to 2040.

4. PRESENT AND FUTURE MANAGEMENT OF SPENT FUEL

This paper ambitions to confirm that whatever the route chosen today and tomorrow, the spent fuel discharged from the power plants are managed according to existing and mature infrastructures and technologies while also protecting human health & environment. The planned disposition of spent fuel is summarized in Fig. 2 based on the fraction of the total t HM of spent fuel that has been discharged to date.

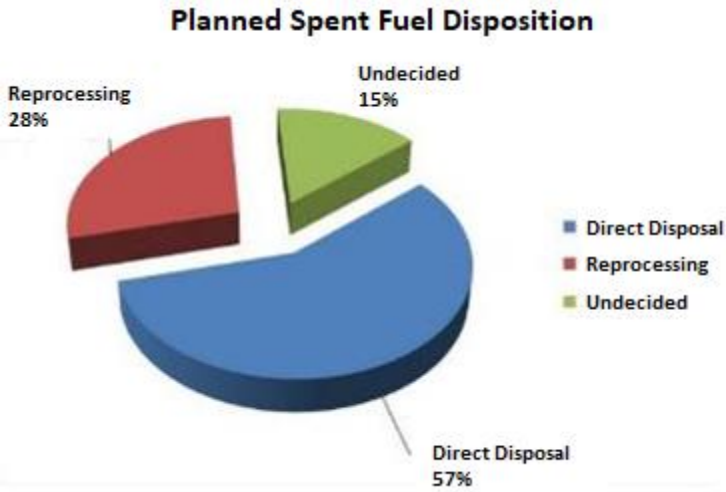

FIG. 2. Summary of existing spent fuel by planned disposition.

The currently envisaged strategies to ensure a safe and cost-effective overall management of spent fuel differ from one country to another and can be described as follows:

The **"open cycle"** or "once through" strategy considers spent fuel as a waste. After a period of interim storage, the spent fuel will have to be packaged to meet disposal acceptance criteria and will be disposed in a deep geological repository.

The **"closed cycle"** (including the "partially closed cycle") strategy considers that the spent fuel provides a potential future energy resource. The spent fuel is reprocessed in order to recover valuable fissile materials (uranium and plutonium). The HLW (along with other wastes such as LLW and ILW) 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.

Besides these reference strategies there are also countries, which either are awaiting a decision on the future strategy to be implemented or consider the open cycle as the current reference while keeping the flexibility to examine and assessing alternative options.

A majority of countries has adopted or uses for reference the "open cycle", while the countries with some of the largest nuclear programs, e.g. France, United Kingdom, Russian Federation, Japan, India and China, have adopted the "closed cycle". Some countries with a small nuclear fleet, like the Netherlands, have also opted for the closed cycle strategy, with reprocessing services provided by one or more of the larger countries with this capability. Some other countries, e.g. Germany, United Kingdom (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) and the United States of America, have changed their policy from "closed cycle" to "open cycle".

The amount of spent fuel from non-power reactors is not dealt with in this paper. It is interesting however to note that some countries are returning its non-power reactor spent fuel to the country of origin of the fuel, mainly Russian Federation and United States of America and that some others, such as Australia, Belgium and Sweden have decided to reprocess their spent fuel.

4.1. The "closed cycle": Reprocessing of spent fuel and reuse of uranium and plutonium

Spent 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 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 and interim stored in a very stable matrix purposely designed for storage, transport and disposal awaiting a future DGR. The main activation products (hulls and end-pieces) from reprocessing are conditioned in a stable matrix and also interim stored awaiting disposal in a DGR

Currently, the countries which operate reprocessing facilities are France, India, and the Russian Federation. India has recycling facilities for both thermal and fast reactor spent fuel in near future and has a unique strategy for using its Thorium reserves in its advanced reactors after breeding U233 in fast reactors. The United Kingdom operated reprocessing facilities for LWR fuel until recently (closed in 2018) and will still operate the Magnox reprocessing plant till around 2020. China is operating a pilot plant and is looking to deploy an industrial facility. Japan is planning to commission in 2021 its Rokkasho-Mura plant. In the past, reprocessing was also carried out by the United States of America. Other countries, e.g. Belgium, Bulgaria, Hungary, Ukraine, Czech Republic, Germany, Italy, Japan, the Netherlands, Slovakia, Spain, Sweden and Switzerland, have used services provided by foreign facilities (in UK, France and the Russian Federation (including during the time of the former USSR)) for the reprocessing of their fuel.

The commercial capacity for reprocessing was 4,800 t of heavy metal in February 2018. It will be temporally reduced and will then increase again as new facilities in the Russian Federation, China and Japan come into operation.

4.2. The "open cycle": Direct disposal of spent fuel

In the "open cycle" option (also known as "once through" or "direct disposal"), spent fuel is considered to be a waste and is stored for several decades to allow the decay heat to be reduced. Before being sent to the DGR, the spent fuel will have 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 spent fuel container may be required.

Different types of geological media and associated engineered barriers are considered. There is presently a broad consensus among technical experts that the preferred method of ensuring long-term safety for HLW and spent 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. Emplacement in carefully engineered structures buried deep within suitable geological formations provides the long-term stability typical of a stable geological environment. At depths of several hundreds of meters, 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. Countries are studying different geological media, depending on availability, for their DGR.

4.3. Drivers for spent fuel management strategies

Countries choosing the "open cycle" have generally no immediate interests or purposes in using the uranium and plutonium recovered from the reprocessing of the spent 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 gives also the flexibility to the nuclear operators to decide in the future whether to continue with the "open cycle" route or to switch to the "closed cycle" route. There will be thus a need for interim storing and at a final stage encapsulating the spent fuel in order to allow for its disposal in a DGR. This latter stage could occur many decades after the spent fuel has been discharged from the reactor.

Some other countries make the choice of the "closed cycle". Generally speaking, the recycling in human activities is considered to be a sustainable approach and is usually promoted at the national level. Recycling in the nuclear industry is then made to take advantage of the valuable material contained in the spent 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 of in the DGR, together with the conditioning in the best available matrix. Moreover, it allows for standardization of HLW package and to ensure saving 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 reactors deployment.

In front of the different strategies described, it is worthwhile analysing the drivers behind these options. Indeed, looking at the economic criteria, the most recent study comparing the competitiveness of "open" and "closed" cycle, the 2013 OECD-NEA study (ref OECD 2013 NEA No. 7061), does not bring an answer to that question since it concludes that these two approaches are economically comparable when fully integrating the total fuel cycle costs:

— The Political/Social driver is related to dedicated decisions taken at the national level, such as the compliance with a law or a directive, the need to manage the public or social acceptance or the deployment of industrial vision taken at the national level;
— 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 or increase/secure their independence towards the uranium supply or ensure proper 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 spent fuel management;
— Indeed, the Economic factor, as analyzed by the here above described OECD study, plays a central role. 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 on an encapsulation facility and provides the nuclear operators the flexibility to decide the spent 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 the reprocessing operations may also impact the overall economy considered.

— The option chosen for the spent fuel management clearly has an Environmental impact. Indeed, the packages to be disposed of in the DGR are encapsulated spent fuel in the "open cycle" route. The encapsulated spent 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.
— The Non-proliferation considerations vary from the "closed cycle" to the "open cycle". In the latter case, the valuable material is contained in the spent fuel to be disposed of, creating thus a need for a safeguards control regime during a period to be determined and in the case of non self-protecting spent fuel, security considerations. In the case of the "closed cycle" route, HLW to be disposed of are free from any safeguards control regime. The separated plutonium having been separated with the objective to be recycled would need to be managed under a safeguards control regime.

Looking at how these drivers will influence the option chosen by a given country, it is important to point out that the spent fuel management strategy is always defined at the national level, even if the nuclear operators are privately owned companies. It has to be underlined here that the main factor leading to the choice of a spent fuel management strategy in the frame of a long-term vision of the overall national energy program is usually driven primarily by the political and country nuclear strategy. Moreover, while recognized as, of course, an important driver, the economical factor is not considered as the primary one. Keeping open the flexibility for later options is also an important factor. This approach could be of interest to the new comers in 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 countries with a large nuclear program, such as mentioned above, have independently implemented their spent 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.

4.4. Challenges and achievements

Section 4.1 which presents the actual spent fuel management provides full confidence that all parts of the back-end of the fuel cycle (interim storage, recycling, transportation, and disposal) are industrially and safely implemented presently and for the next decades whatever the delay in the DGR facilities. Clear progress is being achieved successfully for the implementation of DGR in three countries (Finland, Sweden and France) with defined schedule. It should be recognized that carrying out the construction and operation of a DGR is and will remain slow in many countries. This has resulted in the requirements for much longer interim storage (planned, built and operated as AR or AFR sites) of the spent fuel and HLW until DGR's are available.

However, the progress at the back-end of the nuclear fuel cycle has to face some challenges:

— The length of the storage period could be many decades. As the requirements for storage capacity for spent 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 goes beyond the storage facility itself. The spent 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 spent fuel (fuel integrity after several decades of storage) after a long period of interim storage, especially in dry storage conditions;

— Challenges are also related to the need to overcome concerns caused by major accidents (like Fukushima and Chernobyl) as well as the NIMBY (Not In My Back Yard) syndrome and associated public misinformation;
— Non-proliferation issues related in particular to non self - protecting fuels may raise some challenges.

Many countries are facing delays in their programs for the DGR of spent fuel and HLW. In some cases, the process to find a site has completely restarted, with some countries taking a technical siting approach, while others are taking a voluntary approach or a combination of technical and voluntary. Thus, the time schedules for the DGR have been revised considering delays for reasons such as:

— Identification of the siting activities;
— Public acceptance;
— Technical implementation;
— Regulatory activities due to challenge caused by the lack of experience of licensing such facilities.

In addition, 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 it will extend many decades to a century or more in some cases.

It has to be mentioned here that delays in DGR commissioning do not have the same impact when comparing the “open cycle” and the “closed cycle”. Indeed, in the case of the “open cycle”, the long-term storage of spent fuel may raise specific issues in terms of safety (cladding integrity) or security (physical protection) while the long-term storage of HLW does not raise such additional issues. Proposed timelines for the operations of DGRs varies from country to country but to-date the estimated earliest and farthest year for opening DGR are 2024 and 2160, respectively. Most designs for SNF and HLW disposal are strongly influenced by the heat load of the waste and a reduction in heat load makes the DGR more compact and, in some respects, easier to design. A positive side effect of these 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 facility, triggering stronger and stringer negative views from the public and politicians on nuclear waste management.

5. AN INDUSTRIAL VIEW ON THE R&D AND INNOVATION IN SPENT FUEL MANAGEMENT

There have been essentially three “waves” in the considerations regarding spent fuel management:

— The first 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;
— Given the continued delay in DGR deployment programs, some governments as well as international initiatives studies the options to reduce the amount and radiotoxicity of the waste to be disposed of. Partitioning and Transmutation research seeking the most advanced fuel cycle options aimed at reducing maximally the amount of waste and transuranic content of the wastes;
— In parallel, nuclear industry and utilities continued to deploy new and innovative approaches to further the performance of fuels and the waste arising from NPPs and fuel cycle facilities. These performance gains guaranteed continued competitiveness and compliance with regulatory changes over time.

Today, in a more liberalized and competitive energy market environment while still being exposed to uncertain GDR programs worldwide, the focus on spent fuel management leans towards the reduction of costs and risks from such uncertain spent fuel management futures.

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

There is no shortage on evolutionary and innovative solutions to further improved spent fuel management as shown in Fig. 3.

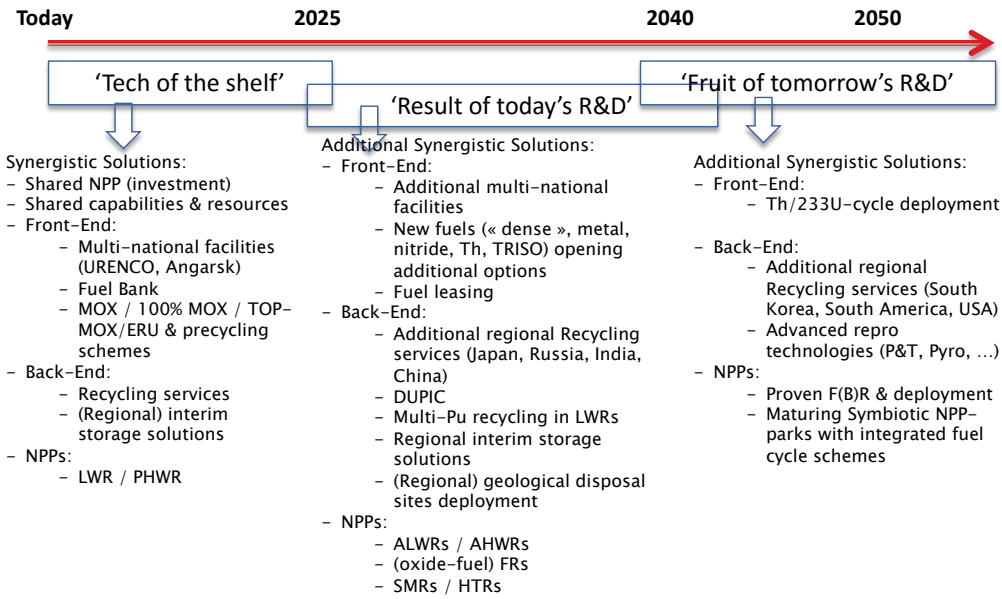

FIG. 3. Overview of synergistic options for improved spent fuel management.

Today's solutions, fruit of R&D in the past, provides already avenues for improved sustainability and spent fuel management in nuclear energy where various power plants and fuel cycle developments may see industrial deployment during the coming two decades as result of today's investments and R&D. Particularly, multi-recycling schemes in LWR/VVERs could be very significant solutions to spent fuel management as significantly reducing their cost and risk exposure.

Choices in tomorrow's R&D will lead to further improvements though mostly geared towards impact in second half of this century.

6. CONCLUSIONS

Industrial infrastructures and technologies are available or planned in order to efficiently and safely secure all spent fuel management steps: storage (wet or dry) (AR or AFR), reprocessing, recycling and transportation (road, rail, sea).

Moreover, overall review/control/monitoring of such management is made in a number of international organizations such as:

— The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management;
— The EC implementation of Directive 2011/70/Euratom;
— IAEA Status & Trends Report on radioactive waste and spent fuel management.

Available or planned infrastructures will allow to safely manage the spent fuel for many decades. However, while being planned in three countries (Finland, Sweden and France) most of the deep repositories projects suffer delays. This being said, the industry has full capacity to mitigate resulting risks or uncertainties and to develop implementable innovation programs to constantly increase efficiency and safety.