

PROCEEDINGS SERIES

Management of Spent Fuel from Nuclear Power Reactors

Meeting the Moment

PROCEEDINGS OF AN INTERNATIONAL CONFERENCE
Vienna, Austria, 10–14 June 2024

MANAGEMENT OF SPENT FUEL
FROM NUCLEAR POWER REACTORS

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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MANAGEMENT OF SPENT FUEL FROM NUCLEAR POWER REACTORS

MEETING THE MOMENT

PROCEEDINGS OF AN INTERNATIONAL CONFERENCE ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
IN COOPERATION WITH THE
EUROPEAN COMMISSION,
THE OECD NUCLEAR ENERGY AGENCY,
THE WORLD NUCLEAR ASSOCIATION
AND THE WORLD NUCLEAR TRANSPORT INSTITUTE
AND HELD IN VIENNA, 10–14 JUNE 2024

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2025

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FOREWORD

Nuclear power can help address the dual challenges of ensuring reliable energy supply and curbing greenhouse gas emissions. Today, there are more than 400 nuclear power reactors in operation, in 31 countries, supplying more than 10% of the world's total electricity. This contribution currently accounts for a quarter of all low carbon power generation globally, and nuclear power will continue to play a key role in the world's low carbon energy mix for decades to come.

The safe, secure and sustainable management of spent fuel from nuclear power reactors is key to the future of nuclear energy. It is a complex undertaking, covering many technological aspects related to the storage, transportation, reprocessing (including high level waste disposal and nuclear products recycling) and disposal of spent nuclear fuel (SNF). Furthermore, research and development has established the feasibility of advanced energy systems to extract additional energy from SNF. These systems have the potential to reduce both the volume and hazard of nuclear waste, while improving the utilization of natural resources.

In recent years, increasing attention has been paid to the development and upcoming deployment of small modular reactors (SMRs) and microreactors. SMRs are new reactors designed to generate typically up to 300 MW(e) of electric power and to be used for non-electrical industrial applications. Much focus has been placed on certain aspects of SMR deployment, such as reactor concepts, engineering, economics, infrastructure and safety, however, the fuel cycle, and particularly the management of spent fuel, has received comparatively limited consideration.

In 2024, the IAEA organized the International Conference on the Management of Spent Fuel from Power Reactors, held in Vienna from 10 to 14 June, with the theme "Meeting the Moment". Special attention was given to the engagement of the younger generation of professionals, recognizing that sustaining the implementation of an SNF management programme is a major intergenerational undertaking. The purpose of the conference was to provide a forum for the exchange of information on national SNF management strategies and on how the management of spent fuel can support the role of nuclear energy in a changing energy mix. With some countries moving towards nuclear energy to mitigate climate change and meet their national energy goals, and others moving away from nuclear energy and concerned about the legacy of its use, the world has reached a pivotal moment. Those responsible for managing SNF need to rise to the challenge of meeting the moment.

Building on the topics of the 2019 conference, the 2024 edition aimed to illustrate the benefits of an integrated approach to the nuclear fuel cycle and its impact on the management of spent fuel from power reactors. It explored the potential implications of deploying advanced reactors, such as SMRs, with new fuel types, through considering technological developments, regulatory requirements, safety, security, safeguards, economics and other relevant aspects. The conference also examined the potential for advances in the management of SNF from power reactors to address current issues, and identified strategies and possible future challenges to be considered in preparation for an evolving energy landscape.

Developing fuel cycles takes time. For those embarking on this process, there is over 60 years of accumulated experience to build on. Innovation throughout the back end of the fuel cycle is essential, not only from a technological perspective but also through new forms of collaboration, such as going beyond sharing research to sharing infrastructure.

This publication provides a summary of the various conference sessions, including opening speeches, four plenary panel discussions (two on national strategies, one on stakeholder engagement and one on innovation and integration) and closing remarks, as well as summaries of the presented papers. All presented papers, listed in Annex II, can be found in the supplementary files on the IAEA Publications web site. Contributions to the four plenary panel discussions have been included in this publication as fifteen extended abstracts and six papers.

The IAEA is grateful to the members of the International Scientific Programme Committee, the Conference Secretariat and the IAEA staff who supported the event, for their commitment, professionalism and engagement. The IAEA also acknowledges the valuable contributions of the collaborating international organizations: the European Commission, the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development, the World Nuclear Association and the World Nuclear Transport Institute. The IAEA officers responsible for this publication were A. González Espartero of the Division of Nuclear Fuel Cycle and Waste Technology and G. Bruno of the Division of Radiation, Transport and Waste Safety.

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1. EXECUTIVE SUMMARY

Nuclear power can help address the twin challenges of ensuring reliable energy supplies and curbing greenhouse emissions. Today there are more than 400 nuclear power reactors in operation in 31 countries, supplying over 10% of the world's total electricity which equates to a quarter of all low carbon power. Nuclear power will continue to play a key role in the world's low carbon energy mix for decades to come.

The safe, secure, and sustainable management of spent fuel from nuclear power reactors is key to the future of nuclear energy. It is a complex undertaking, covering many technological aspects related to the storage, transportation, reprocessing (including high level waste (HLW) disposal and nuclear products recycling), and disposal of spent nuclear fuel (SNF). Furthermore, research and development has established the feasibility of advanced energy systems (advanced reactors and associated fuel cycles) to extract additional energy from SNF, which have the potential to reduce nuclear waste volumes and hazard, and lead to better utilization of natural resources.

There is a lack of clarity regarding spent fuel storage durations, due in part to the long lead time to develop and obtain societal support and license deep geological repositories. This subsequently impacts the handling and transportation of SNF, as well as downstream fuel cycle steps. In this context, the availability of future technologies (including recycling options), underground disposal facilities and suitable financial, regulatory, and political frameworks need to be ensured for the coming generations. Knowledge management and knowledge transfer across multiple generations are particularly challenging. In addition, knowledge retention is important to ensure on-going spent fuel storage and retrieval for final disposal given the timeframes envisaged.

The implementation of SNF management strategies can take decades and allocating the necessary resources to implement them is often difficult. National strategies have to be flexible enough to accommodate potential sociopolitical changes, future options and new technologies that will enhance the safety and sustainability of nuclear power. It is paramount to take an integrated view of the nuclear fuel cycle to ensure that all stages are clearly identified and understood, enabling effective decision making for the back end of the fuel cycle.

The last IAEA International Conference on the Management of Spent Fuel from Nuclear Power Reactors, held in June 2019 under the theme 'Learning from the Past, Enabling the Future', covered all management stages for spent fuel from past, present, and future nuclear power technologies, and how they can be affected by decisions taken throughout the nuclear fuel cycle. SFM'19 conference conclusions highlighted that an effective SNF management programme demands strategic planning to ensure sufficient storage capacity, particularly in light of delays in disposal facility deployment; Technological innovations, such as multirecycling in thermal reactors, offer a sustainable path forward for the transition to fully closed fuel cycles with fast reactors; The importance of learning lessons from the past and developing robust and integrated strategies for SNF management; Early stakeholder engagement, international collaboration, sustainable financing, and effective knowledge transfer to empower the next generation of nuclear professionals are key factors for the successful implementation of a SNF management programme.

During recent years, increasing attention has been paid to the development and upcoming deployment of small modular reactors (SMRs) and microreactors. SMRs represent new reactors designed to generate electric power typically up to 300 MW(e) and to be applied for non-electrical industrial applications (e.g. water desalination and heat generation for industrial processes). While much focus has been given to certain aspects of SMR deployment such as reactor concepts, engineering, economics, infrastructure, and safety, the fuel cycle, and in particular the management of spent fuel, appears to have received limited consideration so far.

In this context, the IAEA organized the International Conference on the Management of Spent Fuel from Nuclear Power Reactors, in Vienna, from 10 to 14 June 2024, under the theme '**Meeting the Moment**'. Special attention was given to the young generation of professionals. As part of the conference, a Young Generation Challenge was announced for professionals under the age of thirty-seven. Young generation involvement is key for sustaining the implementation of SNF management programmes as it is a major intergenerational undertaking. All papers presented at the Conference were peer reviewed and eleven Young Generation winners

(seven females and four males) were selected based on the outstanding quality of their papers, the diversity of topical areas, as well as the geographical distribution. In recognition of their work, each winner was granted to attend the conference in person, to co-chair a technical session, and to contribute to summarizing the session's discussions, which have been included in these Proceedings. In addition, they received a certificate signed by the IAEA Director General, Mr Rafael Mariano Grossi.

The scope of the conference covered all stages of the management of spent fuel from nuclear power reactors past, present and future, (including SMR and microreactor technologies), and how decisions taken in the rest of the nuclear fuel cycle can affect its management. Whether countries are moving toward nuclear energy to mitigate climate change and/or to meet their national energy goals or moving away from nuclear energy due to concerns about the legacy of its use, the world has reached a pivotal moment. Those who manage SNF need to rise to the challenge of **meeting the moment**. The 2024 edition of this conference aimed to illustrate the benefits of an integrated approach to the nuclear fuel cycle on the management of spent fuel from power reactors, and the potential impact of the deployment of advanced reactors (e.g. SMRs) with new fuel types, through considering technological developments, regulatory requirements, safety, security, safeguards, economics, etc. The conference addressed advances in the management of SNF from power reactors to overcome current issues and identified strategies and anticipated challenges to be addressed in preparation for the future.

With this vision the conference was structured into seven tracks covering national strategies for SNF management of countries; storage of SNF and vitrified HLW and subsequent transportability; transportation in the back end of the fuel cycle; recycling of spent fuel; disposal of SNF, HLW and other waste forms in Deep Geological Repositories (DGR); impacts of advanced nuclear energy systems on the back end of the fuel cycle; and achieving integrated spent fuel management (SFM). This is reflected in this publication, which includes: opening speeches; four plenary panel discussions on national strategies (I and II), stakeholder engagement, and innovation and integration; summaries of all presented papers; and closing remarks. All presented papers can be found in the **supplementary** files on the IAEA publication website. Contributions to the four plenary panel discussions have been included in this publication as fifteen extended abstracts and six papers.

Different approaches for managing SNF have been and will be adopted around the world due to a range of technical and societal factors. There is a clear consensus that the management of SNF has to encompass all steps from reactor core discharge to emplacement of spent fuel and/or high level waste in a disposal facility. The prospected growth of nuclear energy goes hand in hand with a growth in the amount of SNF which will need to be responsibly managed. If the use of nuclear energy worldwide is 'tripled', a strategic look at current fuel cycle facilities will be needed to ensure that the transition towards more advanced fuel cycles is kept competitive. There are many new reactor technologies under development, some quite different from the commercial scale plants in operation today and providing not just power but meeting other needs of heavy industry and society at large. To complement this innovation in the front end, there are also needs for innovation in the back end. This could be done for example through utilizing waste from the current reactors to fuel the next generation of reactors or by designing fuel cycles that can maximize the fuels' potential to its fullest.

Sixty years ago, locating and developing nuclear facilities was undertaken on national interest grounds and the local communities were rarely consulted. The promise of clean, plentiful, and cheap electricity promoted the industry. Over time, anti-proliferation movements, concerns over nuclear waste and nuclear events have raised the profile and awareness of the public that nuclear activities represented a risk and installed a mentality in some countries of 'not in my back yard'. To manage these concerns, it grew increasingly important for the industry to engage with the public and to work with local communities through providing information, fostering open dialogue, and being transparent. While there is currently increasing support and acceptance by the public and pressure groups that nuclear power offers benefits in terms of tackling global warming, this is not necessarily the case when it comes to siting fuel cycle facilities and especially waste disposal facilities. The panel on stakeholder engagement brought together a cross section of people from a public representative, a university, and waste management organizations to share their experiences, and approaches to stakeholder engagement.

There is a renewed interest in spent fuel characterization related to spent fuel dry cask loading and in support of spent fuel disposal, as it is important to know the characteristics and properties of the spent fuel because uncertainties impact the design and the cost of storage or disposal facilities. Progress in spent fuel characterization technical basis has focused on technical gaps. This highlighted during the conference the need for experimental investigations through direct measurement of irradiated materials, as well as the integration of novel techniques such as machine learning aimed at reducing uncertainties. Confirmation/generating data in support of spent fuel integrity in storage is important for providing confidence to key stakeholders that the fuel is safely stored and can be readily retrieved and transported in the subsequent stages of the fuel cycle.

Various studies related to spent fuel and several cladding types integrity under wet and dry storage conditions were shared during the conference. The objectives of these studies were to ensure the safety of all relevant operations during storage, prior to disposal or reprocessing or to further understand potential degradation mechanisms. In this respect, studies into understanding the behaviour of hydrogen which goes into solution during the drying of zirconium clad fuels and the form in which it subsequently precipitates during cooling and its impact on clad mechanical properties has attracted much interest over the last decade and continues to attract interest. Overall, there is increased confidence that national or multinational SNF and HLW repository will be feasibly developed. Availability for most countries, however, is still some decades away which is impacting existing nuclear programmes in terms of the need for additional storage or renewal of storage facility operating licences.

Transportation is a key enabler for the back end of the fuel cycle. Planning for transport has to start early enough to ensure that the necessary infrastructure is in place. Some of the fuels from SMRs and all other types of next generation's spent fuels represent significant transport challenges that have to be adequately addressed and not underestimated. Transport has to be considered when developing these new types of reactors. A reactor is worth nothing if its fuel cannot be shipped. International transport of floating nuclear power plants (FNPPs), transportable nuclear power plants (TNPPs) and microreactors is an emerging area and may require changes to the transport regulatory framework for these reactors to be commercially viable. Actions to be anticipated may include stakeholder and public engagement; development of an appropriate regulatory infrastructure, including emergency preparedness and response; design, testing, licensing, manufacturing and commissioning of new casks to accommodate spent fuels with higher enrichment and higher burnups; and ageing management programmes for dual purpose casks during extended storage periods to ensure subsequent transportability.

Reprocessing technologies are moving forward to industrially demonstrate multirecycling in LWRs to stabilize both plutonium stockpiles and SNF inventories without affecting overall reactor operations. Processes for isotope recovery are being developed to produce advanced reactor fuels and transmutation targets for accelerator driven systems with the goal of reducing the volume and hazard of generated waste. Research and development efforts are being applied to reprocess advanced spent fuels such as TRISO particles in pebbles and compacts, and accident tolerant fuels. It was highlighted during the conference that the current industrial reprocessing capacity is limited. It has to be taken into consideration that La Hague plant in France will reach the end of its operational life by 2040 at the same time as when some of the envisaged SMRs are foreseen to be commissioned. During the conference French long term strategy for modernization of France's reprocessing infrastructure in the 2040 to 2060 timeframe was explained.

It is evident that some countries have made significant progress in SNF disposal projects, but slow or delayed siting process remain one of the important impediments for final disposal. Diverse SNF inventory, including SNF from future SMRs and SNF characterization, as well as records keeping and knowledge management are disposal challenges. The conference showed that countries are developing solutions to address those challenges, for example by developing uniform disposal canister systems or by developing the use of machine learning tools. Disposal cost optimization is also important. Regular cost estimation revisions need to be prepared based on clear national policy and strategy. Strategic decisions such as open vs. closed fuel cycle, disposal in mined DGRs vs. deep boreholes, constructing one or more DGRs for existing and future spent fuel arisings are all factors that can significantly impact the costs.

Anticipating the impacts of spent advanced nuclear fuels in the current back end of the fuel cycle programmes is paramount. The chemical form of the spent advanced fuels is the characteristic that has the greatest impact

while their radiological characteristics are similar to those of current fleet's spent fuel. Potential integrated management solutions including interim storage systems, transportation, and spent fuel recycling technologies envisaged by advanced reactor vendors or users have been explored and presented during the conference. These included: the implementation of 'symbiotic fleets' of LWRs and advanced fast reactors to reduce the HLW; the impact of SMRs deployment on multinational cooperation within the back end fuel cycle, including the introduction of a Multinational Repository (MNR); exploring the links between potential SMRs deployment and current nuclear energy programmes; research activities for regulatory readiness for various advanced non-light water reactor fuel types such as metal fuel, TRISO, and molten salt fuel; and the role of 'safeguards by design' through the early engagement with the IAEA Department of Safeguards during reactor and back end technologies development.

Scenario analysis of the energy systems and involvement of various stakeholders in the assessment of SNF management options, identifying key drivers and decision milestones, are crucial in supporting the development of a comprehensive analysis of the various management scenarios. This can help to serve as a basis for assessment of the available options or for technical and financial optimization of projects. For the latter, it is important to use accurate data and properly considered associated uncertainties. Developing a complete and comprehensive long term vision on the nuclear fuel cycle, involving all relevant stakeholders from i.e. industries, technical support organizations (TSOs) and safety authorities, is key. The importance of political support in this context is identified as a key success factor. Recent progress made on the complex task of SNF removal and retrieval of fuel debris at the Fukushima Daiichi NPP highlighted the significance of having an integrated approach.

The development of a complete fuel cycle system, including the management of SNF, takes several decades. Key features in such processes include leveraging experience, dedicated research and development, the sharing of existing infrastructures, the use of assessment and optimization tools, and enabling knowledge and expertise transfer to existing and future generations with the aim to achieve continued public support for implementation of optimized system solutions. All the ongoing research and development will allow the nuclear fuel cycle to reach new levels of safety and sustainability.

All presented papers, listed in Annex II, can be found in the supplementary files on the IAEA publication's individual web page at www.iaea.org/publications.

KEY TAKE AWAY MESSAGES FROM MODERATORS OF PLENARY PANELS

Panel on National Programmes (Session I). Moderator Sama Bilbao y Leon, DG-WNA

- The challenge of spent fuel management is not an emergency, but it is important to provide confidence to the public/stakeholders that spent fuel is being effectively managed, i.e. there is a timeline, milestones, and we are progressing against them.
- The importance of international cooperation. Working together adds value to all parties involved, sharing of infrastructures will add benefits.
- Engaging with the next generation. When communicating with the next generation it is important to show the entire picture. Indeed there is a plan for managing SNF, and the know-how on how to implement it.

Panel on National Programmes (Session II). Moderator Hans Wanner, Hans Wanner Consulting

- The spent fuel management policies differ between the countries represented in this panel.
- While in some countries a decision is pending, others either plan direct disposal or strive for a closed fuel cycle by reprocessing spent nuclear fuel.
- In all cases a deep geological repository is needed, either for spent fuel or for high level waste from reprocessing.

- Postponing the planning of such a repository until a back end policy has been decided needs to be discouraged in view of the long timeframes required for that process.

Panel on Navigating Stakeholders Engagement: Sharing Insights and Lessons Learned in Spent Fuel Management Strategy Implementation in Member States. Moderator Irena Chatzis, IAEA

- There were several common themes expressed during the panel discussion.
- These were related to listening to all points of view, being open, transparent, inviting people in and showing them reality or what you planned to do, allowing them to take the lead so responses could be targeted, install learning, and, above all, keeping communities and public in general informed as the project progresses, from the start to the end of operations.
- Learning from one another is paramount and highlights the importance of sharing lessons learned. Not only in stakeholder engagement but for all aspects of the nuclear fuel cycle development and implementation.

Panel on Innovation and Integration: Approaches for Managing Spent Fuel from Advanced Reactors. Moderator Laura McManniman, EPRI

- The panellists have discussed many aspects of innovation, which are not only technical, and include engagement with stakeholders, international collaboration, sharing infrastructures, etc.
- We need to think about how to innovate collaboratively, how to do it commercially, and how to share infrastructure, all the way through the whole fuel cycle not just only thinking about waste disposal.

MAIN CONCLUSIONS

1. The conference covered all steps of the back end of the nuclear fuel cycle with particular attention being paid to young professionals and the management of spent fuel and wastes from SMRs.
2. To meet net zero carbon targets, nuclear will play an important role in the world's energy mix. The initiatives in support of SMRs, and in particular advanced reactor system back end fuel cycles, have been addressed in terms of the ability to store, transport, reprocess and dispose of generated wastes. Most of these efforts are in the early stages but this provides us with the basis for developing strategies for making decisions on new fuel cycles.
3. Regardless of the national approach or fuel cycle adopted, repositories are needed to manage the waste arising from the fuel cycle whether this is operational, spent fuel or reprocessing wastes. Presentations and discussions on this topic reassured that this is being actively addressed, not only for existing, but also for potential wastes from new fuel cycles.
4. Developing fuel cycles takes time. For those embarking on this process, there is over 60 years of learning to build on. Innovations throughout the back end of the fuel cycle are essential, not only from a technological perspective but also in different collaboration ways, such as going beyond sharing research to sharing infrastructures.
5. Having a geological repository or other type of repository is only one piece of the puzzle, the necessity and benefits of accurate data, undertaking scenario analysis, technology developments to aid repository design, efficiencies, and safeguards are also required.
6. The challenge of spent fuel management is not urgent, but it is important to provide confidence to the public and other stakeholders that it is being consciously and safely managed.
7. Technical solutions can only be successfully implemented if there is social support and political commitment to do so. Continued political commitment and investment is key for the sustainable development of a nuclear programme. Unfortunately, there is a lack of sustained political commitment in most of the countries, however there are some encouraging examples as the French comprehensive long

term vision on the nuclear fuel cycle thanks to such support as well as the progress made in Finland and other countries towards operations at their geological repositories in the coming decade or so.

8. Transportation is an essential enabler in all back end fuel cycle options. Anticipation is key and planning for transport has to start early to ensure smooth transition from one stage to another.
9. Development and implementation of a geological repository is a complex task to be done by a country alone. International cooperation to gain know-how, guidance and learning from existing and previous projects is invaluable. It is though, a time-consuming process and, therefore, early planning is essential.
10. Young nuclear generation is key to the implementation of a spent fuel management programme, as it is a major intergenerational undertaking.

2. OPENING SESSION

2.1. INTERNATIONAL ATOMIC ENERGY AGENCY DIRECTOR GENERAL'S OPENING REMARKS

Opening speech as provided¹.

Rafael Mariano Grossi

Director General, International Atomic Energy Agency

Ladies and Gentlemen, thank you very much for your warm welcome and good morning. What a nice way to start by recognizing the talent of the young nuclear generation. I was told that we were planning to give five awards, but the panel assessing them decided to award seven women and four men, due to the outstanding quality of their papers, the diversity of topical areas, as well as the geographic distribution.

I want to start with recognizing that this is the first time we have started a conference by giving out this type of award, which means that you, the young nuclear generation, impressed us all with your contributions and this really fills us with a lot of hope. One of the things we discuss at these conferences with the Nuclear Energy Agency, World Nuclear Association, and others, is the next generation of nuclear professionals and how to sustain the nuclear industry by ensuring the preparedness of the work force for future undertakings. In this respect, you are going to be leading projects very soon, when the current generation retires. Therefore, the next generation has to be prepared to take over and continue the sustainable development of nuclear energy in the coming decades. This is encouraging, and at the same time we have a recognition that it is not just because there is an increased interest in nuclear power but because we also need to sustain the current activities, which need to be safely and efficiently managed. This is why we need you, the next generation.

Apart from the next generation, what we need to discuss are the issues facing spent fuel management, and by looking at the programme, I am very excited by the thematic depth and focus of the conference programme. I would like to recognize the hard work of the international scientific programme committee in putting this together and for the range of issues which will be addressed during the next five days.

Dear colleagues, with an audience like this I should not be saying obvious things. However, I believe that this is precisely the moment that we should be discussing and focusing our attention on issues and challenges in spent fuel management. Ranging, of course, from the behaviour of fuel cladding to transportation and final repositories, things that we already tackle and have representatives of in this opening session. And we are seeing increased interest in these areas, as we are already experiencing in other areas of the nuclear power industry. The projected increase in nuclear power generation will lead to an increase in the amount of spent fuel to be stored, reprocessed or treated, and disposed of which means that we need, as a community, including industry, regulators, organizations, operators, academia, to be in a position to provide the necessary answers. As you know, wherever we go, the issue of spent fuel and radioactive waste is always put in front of us as one of the challenges and even a reason why some feel nuclear should not be part of the future. So, we need to recognize that and face it. We have a good story to tell, and you are the ones that are going to be telling this story and discussing these challenges.

I am also very happy to be organizing this in cooperation with the Nuclear Energy Agency, the nuclear operators represented by the World Nuclear Association, the European Commission's Joint Research Centre, all institutions which support the industry as well as with the World Nuclear Transport Institute, as transportation is an important enabler of the back end of the nuclear fuel cycle. All of us are behind you.

The last Conference on this topic took place in June 2019. I was not Director General then and many things have happened since. When we look back to June 2019, although it seems like yesterday, there is a sea of difference when it comes to developments in the world. Quite clearly, we are in a world where nuclear is finally, and after many decades, being recognized as part of the global solution to reaching net zero carbon

¹ These remarks have been edited for clarity.

emissions and therefore should be accelerated side by side with renewables. There are many factors influencing this which will determine the success and what we are able to do to achieve it. I cannot think of one factor as important as how we deal with spent fuel. So, we will be following your deliberations with enormous interest. I thank you, and I also thank all our sister organizations working with us. The nuclear community needs to deliver, and to deliver we have to work as one. We need to have a coherent message and sense of direction. While this may seem obvious, it is not in a world that has the challenges that we are facing.

So, I think we need to have the wisdom to think above the difficulties of the day because what we are discussing is an industry that is going to be shaping the world over the next twenty, fifty or more years. So, thank you very much for being here with us. I am really looking forward to the deliberations and of course, the conclusions that you will arrive at.

Thank you very much!

2.2. DIRECTOR GENERAL ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT – NUCLEAR ENERGY AGENCY’S OPENING REMARKS

Opening speech as prepared for delivery.

William D. Magwood IV
Director General of the OECD Nuclear Energy Agency

Shifting Landscape in Nuclear Energy

The global situation has changed considerably since the last edition of this conference four years ago. Nuclear energy is experiencing a global resurgence, with many countries turning to nuclear power for energy security and climate challenges.

At the ‘Roadmaps to New Nuclear’ ministerial conference last September, which was organized by the NEA and the French Minister of Energy Transition and chaired by US Secretary of Energy Granholm, twenty energy ministers and more than 30 industry CEOs gathered to highlight the critical role of nuclear energy in global energy challenges and set about practical paths to address cooperatively the most urgent challenges to expansion of nuclear capacity.

This event set the stage for the global community to take steps past talking about the issues and to focus on collaborative solutions—particularly to the financing of new build, assuring the development of a strong industrial supply chain, and addressing the very difficult matter of assuring that we have the human capacity needed to support our ambitions.

The strong consensus generated at the first Roadmaps to New Nuclear ministerial set the stage for 24 countries to agree to a declaration at COP28, based on NEA analysis, to triple nuclear energy by 2050 to reach net zero.

These developments are most encouraging, as were the outcomes of the Nuclear Summit earlier this year highlighted by DG Grossi. But we all recognize that much work remains. At the second Roadmaps for New Nuclear ministerial this September, we will take the next steps toward closing the gaps that still face us.

The interest in nuclear is very broad and very deep. Many OECD countries have turned to nuclear as a vital part of their energy strategies as well as many nations in the global south.

We are working with our members and key partners such as China, UAE, and others to support this important progress and will engage with countries in Africa through the Common Journey initiative. We look forward to cooperating with the IAEA as this work moves forward.

The NEA SMR Dashboard, which tracks the progress of all the SMR and Generation IV technology development projects around the world, highlights that there are 56 verifiably active SMR projects. As reflected by the analysis presented by the Dashboard—which, by the way, should go live online as digital resource to the world later this year—a very significant number of technologies will be available to the market by 2030 or so. This is vital to the success of the global energy transition and the goal of Net Zero by 2050.

Importance and Complexity of Spent Fuel Management

I am convinced that advanced SMRs and gigawatt-scale light water reactors, alongside other energy technologies, provide the world with a viable, realistic, and practical—though not easy—path to Net Zero.

While we have to deal with a range of challenging front end issues—like financing and supply chains—the effective management of used nuclear fuel is essential.

I have stated for many years that nuclear waste is not a crisis—it is a responsibility and one that that we have time to address. Today’s nuclear wastes are safely and cost-effectively stored and with the use of dry storage technologies, used fuel can be safely maintained for many years.

But it is our task and our generation’s responsibility to make as much progress as possible today and to create the plans to dispose of these materials safely and effectively. We cannot leave the problem to the future.

Gatherings like this one are important because we know there are solutions to all these challenges. At the NEA, we believe that there are many opportunities for collective action and cooperation. We have barely scratched the surface of what is possible for us to work together to build confidence among policymakers and public stakeholders that used fuel is not an endless curse but is, in fact, the best managed waste from any industrial process.

First, and most importantly, countries are making significant progress toward establishing deep geological repositories for the disposal of used nuclear fuel and high level waste.

Finland is scheduled to commission its DGR by next year, Sweden’s licence application for the construction of a DGR was approved in 2022, France submitted their construction licence for a DGR in January 2023, and Switzerland chose the region for site selection in 2023.

These successful efforts are to be lauded and, where possible, emulated. We have many lessons learnt to share.

The most important lesson is to recognize that managing nuclear waste is not just a technical endeavour. It is also an act of social responsibility. As such, many of the lessons from successful programmes are less about the technical aspects of designing and implementing DGRs and much more about the public policy and stakeholder engagement aspects that enabled progress.

The NEA has placed great focus on highlighting the best approaches to stakeholder involvement.

Pioneering work by the NEA Forum on Stakeholder Confidence (FSC) over the years has led the application of social science to decision-making in the nuclear field. The FSC’s work has been truly ground-breaking in its early consideration of topics like the impact of social media and how to involve young generation stakeholders. This experience is shared through the FSC’s insightful reports and flyers as well as through its numerous national workshops.

In addition, our most recent high level Stakeholder Involvement Workshop on Optimisation in Decision Making highlighted more insights from across the nuclear sector reflecting the need to structure all key decisions as mutual learning processes in which all parties can learn and contribute, as well as key input from NGOs about the ‘power balance’ between authorities and stakeholders.

The next workshop will be held early next year and will focus on how to apply these concepts. The NEA’s new High-level Group on Stakeholder Engagement, Trust, Transparency and Social Sciences, chaired by former Canadian Nuclear Safety Commission (CNSC) president Rumina Velshi will be deeply involved in planning this event and will bring a policy-level perspective to this vitally important topic.

It is important to emphasize that all of this engagement is built on a strong international scientific consensus about the safety and effectiveness of DGRs. We are in the position to make clear and unambiguous statements about the safety of DGRs despite the very long time frames involved.

Shaping back-strategies for advanced systems: the WISARD project

But the more than 40 years of research and analysis that informs our confidence in DGRs is based in large respect on conventional nuclear wastes.

For many of the 56 SMR and Generation IV projects that are moving toward deployment, we will need to build that same level of confidence—but instead of decades, we need to accomplish this in just the next few years.

New reactor concepts will lead to a greater variety of spent fuel and waste and will require much more flexibility and adaptability from the entire waste storage, transportation, funding, and disposal systems.

What are the requirements to dispose of fuels that incorporate materials such as graphite or sodium? Can we use existing transport casks or do we need to create new ones? Can planned DGRs accept used fuel from all Generation IV reactors? How will the costs of adapting existing systems to new wastes be recovered? And how do we consider those advanced designs, such as molten salt reactors, which will likely change how we view the nuclear fuel cycle?

Recognizing these critical questions, the NEA is launching an ambitious project called Waste Integration for Small and Advanced Reactor Designs—or WISARD—to explore the back end implications of these new technologies while we are in the design phase.

The WISARD project will incorporate a groundbreaking international effort to promptly assess compatibility with existing waste management solutions and pinpoint areas requiring future innovation to accommodate Generation IV small modular reactors.

WISARD will bring together participants from across the nuclear lifecycle, including advanced reactor developers, government bodies, waste management organizations, regulators, research institutions and industry.

The preparatory phase of this project is underway with a view to start work in early 2025. Should you be interested in learning more, please speak with Rebecca Tadesse who is leading this effort and who will be with this conference over the next few days.

Conclusions

The nuclear energy sector has a tremendous opportunity to play a driving role in the coming energy transition.

This success is not simply the success of nuclear, but the success of our generation's effort to deal with the climate crisis. Without a major contribution of nuclear technology, I believe the prospects of reaching Net Zero are dim if not entirely out of reach.

We need to be prepared for new thinking and new approaches. As such, I conclude by leaving you with three things to have in mind over the next few days:

- We have to embrace the challenge and promise of advanced recycling technologies. Many companies and governments are concluding that integrating these technologies into the future is necessary and inevitable. This will require new thinking about safeguards and non-proliferation and the IAEA will be critical in these deliberations;
- The concept of multinational repositories has to be on the table. Despite the technical and economic logic of shared repositories, we all recognize the political difficulty of this approach. Nevertheless, the NEA is helping countries take initial steps through an effort known as MIRA (Multinational Infrastructure for Managing Radioactive Waste). This multinational project will explore a range of collaborations to support national programmes but will also explore dual-track options for DGR development;
- Finally, we all need to emphasize that the time for talking is behind us. On many critical path issues, we have to act as soon as possible. The right future, with energy security and economic development for all, and a healthy environment will not come on its own. We have to work collectively to bring that future about. Given the size of the challenge and short time frame remaining to act, we have to work as a global community, east and west, north and south. Success will be our collective success; failure will be our collective failure.

2.3. DIRECTOR GENERAL WORLD NUCLEAR ASSOCIATION'S OPENING REMARKS

Opening speech as prepared for delivery.

Sama Bilbao y León

Director General of the World Nuclear Association

Dear Rafael, Dear Bill, Dear Jose Antonio, Dear Ulla, Dear Peter, Excellencies, Distinguished Guests and Esteemed Colleagues, dear friends of a more sustainable future.

Good morning! Thank you to the IAEA for the invitation to join all of you today and bring the point of view of the global nuclear industry. I also want to thank and congratulate the two IAEA Scientific Secretaries, and the entire IAEA Team for putting together a very comprehensive and forward looking programme for this 2024 International Conference on the Management of Spent Fuel from Nuclear Power Reactors. I think we all are going to have a very fruitful and enlightening week.

The title of this conference is 'Meeting the Moment'. An incredibly well chosen title.

Because indeed, this is the nuclear moment!

In the last couple of years nuclear energy has seen a significant resurgence. Policy makers, energy thought leaders, the finance community, end energy users, media and civil society are recognizing both the enormous contributions of the existing nuclear fleet, and the essential need to accelerate the deployment of new nuclear for energy security and independence, and to meet Paris Agreement targets in a cost-effective and equitable manner. Last December in Dubai at COP28 World Nuclear Association launched the NZN initiative and as a result we saw heads of state and high level officials from 25 countries coming together to boldly call for the ambitious goal of tripling nuclear capacity globally by 2050. And then more than 120 companies from the global nuclear industry accepted the challenge and pledged to accelerate efforts to meet the 3x nuclear capacity commitment. Earlier this year, at the IAEA Nuclear Energy Summit in Brussels, that commitment was reinforced once again. We have seen similar support stated at the recent G7 in Turin, IEA 50th Anniversary Ministerial, and at last year's NEA roadmaps for new nuclear summit.

Dear colleagues, there is no doubt that that nuclear energy has the attention of the policymakers. The nuclear industry is at a tipping point... If we make the most of this opportunity and we are able to continue to operate the existing fleet safely and cost-effectively, and we deploy new nuclear with speed at the needed scale, we will trigger a watershed moment and we will witness nuclear energy developing to its full potential. But we have a finite window of opportunity. If we fail to deliver in early projects and in demonstration projects, we will lose the interest of decision makers, who will realize that the nuclear industry is not good at fulfilling promises.

In other words, we have to MEET the MOMENT.

A lot of the focus right now seems to be in development and deployment of new reactors, whether they are traditional large reactors or more innovative SMRs, Advanced Reactors or Microreactors. As I said... it is indeed essential that we deploy these technologies on time and on budget. At the same time, we cannot forget the rest of the nuclear fuel cycle and certainly we cannot forget the entire lifecycle of these facilities. This means assessing every stage from raw material extraction, manufacturing, and operation to decommissioning and used fuel management. Such a comprehensive evaluation ensures that all environmental, economic, and social impacts are considered, promoting sustainability and reducing negative outcomes. In this regard, nuclear energy is unique in its approach as the nuclear industry meticulously plans every aspect of the nuclear fuel cycle and its associated activities. Tripling global nuclear capacity requires sustainable and appropriate back end fuel cycle strategies.

At World Nuclear Association, we are proud to connect the industry's expertise in this area under our Used Fuel Management Working Group. The Used Fuel Management WG promotes sound, safe, sustainable and

proliferation-proof used fuel management. The global experts that contribute to the work of this WG shape industry positions with a view to engaging in the international debate on sustainable management strategies for the back end of the fuel cycle.

In nuclear we have always taken sustainability very seriously. The management of used nuclear fuel, along with any ultimate waste arising from it, represents a well-established industrial activity that has been conducted safely and responsibly since the inception of the civil nuclear industry in the 1950s. While ongoing research and development efforts in this field aim to continuously enhance technologies and processes, current and prospective nuclear power generators can, and do, effectively manage used nuclear fuel using existing practices.

Used Nuclear Fuel is not an obstacle for the expansion of nuclear capacity... quite the opposite I would contend... our historical management of used nuclear fuel is one the best news about nuclear energy, and perhaps we can be bolder telling this success story. We are the only industry that has always had a technology plan for all our leftovers, including recycling, reprocessing, and long term disposal of any ultimate waste product. Very importantly, nuclear energy is today the only one that includes the cost of managing used nuclear fuel in the price of the energy it sells. Unlike other sources of power generation, used nuclear fuel may be reprocessed and recycled to provide added value as an energy resource, which allows for the recovery of valuable materials and reduces the volume and radiotoxicity of nuclear waste. This approach aligns with the principles of circular economy and resource efficiency.

Reprocessing and recycling have been widely deployed to extract the uranium and plutonium contained in used nuclear fuel to provide fresh fuel for existing and future nuclear power plants. Other valuable materials can also be extracted for non-power uses, for example for nuclear medicine.

Whether a country chooses an open or a closed fuel cycle, it is essential that a clear strategy is laid out and implemented including specific milestones and timelines. Public perception plays a crucial role, and the industry has to continue to build trust and understanding with civil society through transparent communication, education, open dialogues, providing accurate information about technological advancements, safety measures, and the sustainability of nuclear energy. On the other hand, changing policies and unnecessary prolonged delays will erode public confidence and potentially undermine nuclear power's role in combatting climate change.

While we have the competency and solutions to manage used fuel today, we can never stand still. Striving for continuous improvement is the only guarantee of sustainability. The global nuclear industry is continually innovating to promote enhanced fuel performance along with better management of radioactive waste while improving nuclear safety culture. These advancements achieved today will provide the impetus for tomorrow's enhancements in nuclear energy and radioactive waste management.

For example, various novel reactor technologies have different challenges for the management of used nuclear fuel. To address these challenges, we are working with AMR developers as early as possible, to ensure that they plan their nuclear fuel cycle strategies, including the back end. This will help in the successful deployment of their new technologies by ensuring that all aspects of the fuel cycle, from fuel production to waste management, are adequately planned and managed.

It is apparent that the options of either recycling or direct disposal are expected to remain as the fundamental pathways for the management of used nuclear fuel in the future. However, there are other avenues that are being researched and developed to complement these options including Advanced recycling fuel cycle options such as multirecycling or transmutation of minor actinides and Deep borehole disposal technologies.

I will close by reminding all of us that all this incredibly important work will require a talented workforce. It is essential that we, as an industry, make a significant effort to inspire, attract and retain the next generation of leaders and experts in used nuclear fuel management, while we facilitate the exchange of knowledge between generations, and while we make sure that our industry becomes inclusive and welcoming of a diverse and gender-balanced workforce.

As we get ready to meet the moment and deploy a large amount of new nuclear, we should ensure the development of a well-structured plan that takes account of forward-thinking technologies coupled with realistic financing models to provide needed protection to the environment and human health. Given the ambition of tripling nuclear capacity by 2050, collaboration at the governmental level and among industry players in recycling, reprocessing, and multinational repositories are essential for sustainable solutions for used nuclear fuel management.

For the first time in quite a while, nuclear energy has an opportunity to make a significant contribution to humanity and planet. The efficient and safe management of radioactive waste and used nuclear fuel is one of the key enablers of that ambition. It is up to us to meet the momentum and deploy the full potential of nuclear energy.

The science and technology of engineered underground repositories, often referred to as deep geological repositories (DGRs), is well-understood and some countries are progressing towards their operation. Many geologies are suitable for final geological disposal of used fuel or vitrified high level waste. Some countries (including Finland, France, and Sweden) have gained societal acceptance for DGR sites, whereas other countries are finding the siting process to be challenging. In the USA, the Waste Isolation Pilot Plant (WIPP) deep geological disposal facility for defence-related transuranic waste has been in operation since 1999.

Many countries, including Belgium, France, Germany, India, Russian Federation, UK, and USA, have operated reprocessing facilities for commercial used nuclear fuel. France's La Hague site fulfils its domestic reprocessing needs and offers reprocessing /recycling services to other countries. Russian Federation's RT-1 has been reprocessing commercial used fuel for several decades. The UK carried out reprocessing of domestic and foreign used nuclear fuel mainly at Sellafield but ceased operation of all reprocessing activities in 2022. In Japan, a reprocessing plant has been built at Rokkasho but has not yet started commercial operations.

Interim storage and DGR

Until a deep geological repository is operational, used nuclear fuel will have to be placed in interim storage at the reactor site or in a centralized facility. While interim storage is technically feasible, it does raise a concern that the storage of the fuel is not the final solution for it. This is why, echoing the comments of my fellow panellists, a state should proceed with siting, constructing, and operating a deep geological repository without unnecessary delay, or they should consider used fuel reprocessing.

If we look at the data regarding the deep geological repositories, the start of final disposal is not imminent in most cases. Projects in France, Sweden, and Finland are the most advanced countries where engaging and communicating across a wide range of audiences and platforms to involve citizens in developing deep geological disposal projects has taken place. Again, referring to the theme of the conference, there are lessons here from the past that can meet the moment.

While we can claim to have solutions today to manage used fuel, we can never stand still. Striving for continuous improvement is the only guarantee of sustainability. The global nuclear industry is continually innovating to promote enhanced fuel performance along with better management of radioactive waste while improving nuclear safety culture. These advancements achieved today will provide the impetus for tomorrow's enhancements in nuclear energy and radioactive waste management.

Innovation

It is apparent that the options of either recycling or direct disposal are expected to remain as the fundamental pathways for the management of used nuclear fuel in the future. However, there are other avenues that are being researched and developed to complement these options including advanced recycling fuel cycle options such as multirecycling of valuable materials; Additional advanced options such as the transmutation of minor actinides and deep borehole disposal technologies.

The development of small and advanced modular reactors providing electricity as well as energy for process heat, desalination, remote industries such as mining, and potential other non-electricity generation purposes, will be secured with similar used nuclear fuel management options as those listed above. Nevertheless, various novel reactor technologies have different challenges for the management of used nuclear fuel, with different life-time costs which should be factored in when considering new technologies. To address these challenges, our working group aims to engage as many SMR developers as possible, and as early as possible, to ensure that they plan their nuclear fuel cycle strategies, including back end. This will help in the successful deployment of their new technologies by ensuring that all aspects of the fuel cycle, from fuel production to waste management, are adequately planned and managed.

Conclusions

In conclusion, it should be recognized that the infrastructures and technologies are available to provide for the efficient and safe management of radioactive waste and used nuclear fuel. The generation of used nuclear fuel, by-products of the operation of nuclear reactors, should not be a barrier to the deployment of new nuclear projects, as solutions for its sustainable management currently exist and innovative options for the future are being developed. Nuclear industry has successfully managed used fuel and corresponding waste for several decades. Given the expansion of nuclear power, the nuclear industry is well-prepared to continue doing so efficiently and safely.

- Used Nuclear Fuel is not an obstacle for new nuclear builds;
- Tripling global nuclear capacity requires sustainable and appropriate back end fuel cycle strategies;
- (Message for AMR/SMR vendors): If AMR/SMR developers plan their nuclear fuel cycle strategies, including back end, this will help the deployment of their new technologies;
- Nuclear industry has successfully managed used fuel and corresponding waste for several decades. Given the expansion of nuclear power, the nuclear industry is well-prepared to continue doing so efficiently and safely;
- Collaboration at intergovernmental level and international cooperation in reprocessing, recycling, and multinational repositories are essential for sustainable solutions for the used nuclear fuel management;
- These actions will enhance the credibility of nuclear energy and boost public confidence.

2.4. DIRECTOR JOINT RESEARCH CENTER - EUROPEAN COMMISSION NUCLEAR SAFETY AND SECURITY'S OPENING REMARKS

Opening speech as prepared for delivery.

Ulla Engelmann

Director of Joint Research Centre-European Commission D-Nuclear Safety and Security

Ladies and Gentlemen,

I am honoured to address you today representing the Joint Research Centre of the European Commission. The Joint Research Centre (JRC) is the European Commission's Science and Knowledge Service. It was established by the Euratom Treaty as a Joint Nuclear Research Centre more than 60 years ago. Our mission is to provide independent evidence, based on knowledge and science, supporting EU policies to positively impact society. We offer scientific expertise and competences from a very wide range of scientific disciplines that cover almost all EU policy areas of interest, including the safe management of spent fuel.

In the European Union, each Member State decides its energy mix. Currently 12 Member States operate 100 nuclear reactors that supply around a fourth of all electricity consumed by the EU. Currently 17 Member States of the EU manage spent fuel in their territory.

As part of the EU framework (the most advanced legally binding regional framework for nuclear safety, waste and spent fuel management, and radiation protection), the Radioactive Waste and Spent Fuel Management Directive 2011/70 of the Euratom establishes a comprehensive common framework for the responsible and safe management of spent fuel.

The primary objective of the directive is to ensure the highest levels of safety and protection for the human health and the environment. This includes setting out requirements for the nuclear facilities, as well as for the safe storage, transport, and disposal of spent fuel. Another key objective of the directive is to promote the harmonization of EU national policies and practices related to the management of spent fuel between the Member States of the EU. This is achieved through the establishment of common principles, criteria, and requirements that Member States have to adhere to in their national strategies. It also establishes the obligation of having national programmes for the implementation of spent fuel policies.

Based on Member States information, the European Commission prepares periodic reports on the progress of implementation of the Directive, including an inventory.

Up to 2019, 55 600 tonnes of Heavy Metal of spent fuel have been produced in the EU. All of it is stored, as there are no disposal facilities in operation, and 900 tonnes of this spent fuel were sent for reprocessing outside the EU; they will return to the EU when the process finishes. It is expected that by 2030 the spent fuel inventory will increase by approximately 20%.

In the period 2017 to 2023, all Member States completed a peer review mission of the Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation (ARTEMIS).

Positive conclusions resulted from the evaluation of the implementation of this legal framework: spent fuel is managed safely in the EU Member States. The system of self-assessments and international peer reviews appears consistent with the needs and is driving updates and continuous improvement in waste management; it is worth remarking that this is best practice on a global scale.

So far, Finland, France, and Sweden have made significant progress in constructing deep geological repositories; they are expected to become operational during this decade and the next one; in the rest of the EU, geological repositories are expected to be ready in the second half of the century. It is a complex, long term process in which continuous efforts towards transparency and public participation play an essential role.

The issues to address include programme control, funding, and updating cost assessments. For that, the European Commission recommends accelerating national programme reviews and updates.

A relevant requirement set by the Radioactive Waste and Spent Fuel Management Directive is related with the research on spent fuel. The directive promotes the exchange of information and expertise between Member States and other countries, and also encourages Member States not only to promote national research programmes, but to support and participate in international collaborations.

Related to this point, I am delighted to highlight the active role played by the JRC laboratories and staff on spent nuclear fuel research. In full alignment with the requirement set by the Radioactive Waste and Spent Fuel Management Directive, the JRC, implementing the Euratom Research and Training Programme framework, has been at the forefront of research in this field, contributing to the European effort with innovative solutions and cutting-edge technologies that contribute to the overall advancement of nuclear safety and security.

Our research on spent fuel covers a comprehensive range of topics, focusing on extended interim storage, deep geological disposal, and accident conditions. The JRC is committed to developing a thorough understanding of the behaviour of spent nuclear fuel throughout its entire life cycle, from its discharge from the reactor to its final disposal.

In our research facility in Karlsruhe, Germany, equipped with state-of-the-art hot cells for the experimental characterization of spent nuclear fuel, we conduct experiments and analyses that contribute to a safer management of nuclear waste. Our research contributes to assessing the mechanical integrity of spent fuel rods and the radionuclide mobility during and after extended interim storage. The JRC facilities allow us to investigate the properties and behaviour of real spent fuel in accident scenarios, as well as the corrosion behaviour of spent fuel materials exposed to groundwater under repository conditions.

By leveraging synergies among the JRC's nuclear research lines and competencies, including those on nuclear data, fuel cycle strategies, partitioning and transmutation, and final radioactive waste forms, we aim to advance knowledge and understanding of spent nuclear fuel management and disposal.

In addition, the JRC is actively involved in research related to the decommissioning of nuclear facilities. It is essential that these facilities are safely and efficiently decommissioned, minimizing the risks to the environment and to human health. The JRC's expertise in this area ensures that decommissioning processes are thoroughly assessed and optimized, contributing also to a sustainable management of the resulting nuclear waste.

In conclusion, there is a renewed momentum for nuclear energy as countries strive to meet their climate goals and achieve strategic autonomy. As nations consider Small Modular Reactors and advanced systems, it is crucial to properly understand and manage the back end of the nuclear fuel cycle. The trust of the society in the safe handling of spent fuel is essential, and research plays a vital role in ensuring this. The EU's legally binding framework for the safe and responsible management of spent fuel propels the national programmes towards final disposal, emphasizing the need for adequate resources and a skilled workforce to establish and strengthen a solid and up-to-date knowledge basis. By investing in research and development, we can contribute to ensure a sustainable and secure future for nuclear energy.

2.5. SHIPPING NUCLEAR TRANSPORT SOLUTIONS DIRECTOR AND WORLD NUCLEAR TRANSPORT INSTITUTE BOARD MEMBER'S OPENING REMARKS

Opening speech as prepared for delivery.

Peter Buchan

Director of Shipping Nuclear Transport Solutions and
Board Member of World Nuclear Transport Institute

Thanks very much to my fellow panel members and for the inviting me to speak today.

Firstly, I think it is absolutely fantastic that the YGE are here. It is a recognition of the good work that young people do. It is just a pity that I do not qualify anymore. I am 54 years old and I think I am young. But anyway, I have two roles. I work for Nuclear Transport Solutions. We are the transport pillar of the UK's Nuclear Decommissioning Authority. We are responsible for rail movements of radioactive materials (RAM), design and licensing of RAM transport containers and sea movements of RAM. I am the Managing Director of our Shipping Business responsible for our ships, marine terminal, and any major marine transport projects. I am also a board director of WNTI. WNTI is a non-governmental member driven organization. We have observer status at the IAEA and consultative status at the International Maritime Organisation (IMO). We work for our members to influence regulatory change and represent their interests in that area. We also develop information and educational tools on all aspects of radioactive material transport to spread knowledge and best practice. We help to keep nuclear moving.

That is one of the key things that I want to leave with you today. Many things have been said, and there are many intelligent people in this room discussing the future of spent fuel management, who have worked in spent fuel management for years and will for years to come: however, please do not forget about the transport element. Because if you cannot transport anything, you cannot do anything. So please do not forget about it.

Did you know that there are fifteen million transports of radioactive materials every year, all around the world? And I tried to find out from ChatGPT how many companies are involved in this, and ChatGPT needs to work a little bit better, because it just said hundreds.

But we do know that this is across tens of countries and hundreds of companies. We sometimes forget these stats and how many industries rely on radioactive materials and importantly a great track record to keep going. Fifteen million transports a year! And we have had no major incidents in decades and decades and decades.

What that is down to?

It is about good designs. Really good technical people designing systems.

It is about great regulation. Because without great regulation we cannot move things; we cannot get the confidence of the people in our communities in which we are moving RAM.

It is about professional operations. Doing the job right, following processes. Having the processes set up right.

It is about collaboration. The whole point of today and this week is about collaboration.

And also, maybe, it might have been a bit of luck as well. I have got no evidence that this is the case, but we certainly do not want to rely on luck. What we have to do is to work really hard to make sure that luck does not play a part in that.

And if you think about it, one incident, just one incident, could bring a network down for quite some time. The knock-on effect of this is considerable and costly. We would have to investigate thoroughly, but it would also be costly in terms of reputation and confidence. That is what this is all about too. It is about having people

understanding that the confidence that people have in nuclear can be affected by one small thing if it is not handled properly.

That affects not just the power generation industry. It affects hospitals, food supply chains, construction, etc.

Nuclear plays a massive role in the world. And we have got a twin challenge.

Firstly, this conference is about tomorrow, but we cannot take our eye off the ball today. We have to make sure that everything we do today is fit for purpose and works well. It is really easy to concentrate on the exciting new stuff, but we have to make sure we do things well.

We also have to plan for the future now. Do not forget about transport. In my experience, and I have been in the industry for thirty-two years, I have always felt that transport is a bit of an afterthought in the nuclear value chain. We need to make sure it is not.

Nuclear Transport Solutions and WNTI regularly get questions from companies that want to move material from A to B, but do not quite know how. In the future we should not really be asking those questions. We should be building it into the value chain now.

Nobody can do this on their own. We need all the companies, we need all the organizations like the OECD/NEA and the IAEA to work together to do this. WNTI can play a role too, as an independent authoritative voice enabling us to keep nuclear moving. We have been around for twenty-five years and have nearly fifty members. Amongst these members, we have world renowned experts who can spread the word and spread the knowledge. And because we have observer status at the IAEA and consultative status at the International Maritime Organization, we can be at the heart of enabling and shaping how regulations work.

That's not about lowering standards. Lowering standards is not where we want to be. It is about supporting an enabling approach to regulation. Our industry will need this more and more as we go forward. Industry and regulators working together, working on how you operate facilities and working on how you transport materials safely, securely, and reliably between those facilities.

From the transport perspective where do we have challenges?

We need **resilience** in the system. We need to make sure that we are passing on the knowledge we have gained in the last fifty or sixty years. It is not only how we pass that knowledge on to the next generation, but also how we encourage more of our younger people to get involved in our industry. Not just in research but in operations, in best practice and making sure that we do things right. I think that is a real challenge for the industry, because if the industry is going to meet its plans going forward it needs a lot of people.

The other thing we need to consider is **regulation**. We need to work closely to develop enabling regulation for the future fuels that will need management. If you are going to routinely move spent future fuel from reactors in a commercially viable way, you are going to have to think how we do this from an enabling regulation perspective, particularly a security point of view. Because today it would be really difficult to do.

And finally, we have to consider how we ensure we transport **sustainably**. Nuclear plays a key part in meeting the world's carbon net zero challenges etc, but if we are going to grow, we are going to be moving things around a lot more. So, we need to think about how we do that sustainably.

This is a great conference. I think it is brilliant that we have people from all over the world in Vienna. My key message is do not forget about transport. It is a key part of the value chain.

Thank you very much!

2.6. CONFERENCE CHAIRMAN'S OPENING REMARKS

Opening speech as prepared for delivery.

Jose Antonio Gago

Former General Manager, Asociación Nuclear Ascó – Vandellós II (*retiree*), Spain

Good morning, ladies and gentlemen. Good morning, dear colleagues. I am delighted to welcome you all to the 2024 Edition of the International Conference on the Management of Spent Fuel from Nuclear Power Reactors, SFM24: **Meeting the Moment**, hosted and organized by the International Atomic Energy Agency, in cooperation with the OECD Nuclear Energy Agency, the European Commission, the World Nuclear Association and the World Nuclear Transport Institute. First of all, I would like to thank the main leaders all these organizations to have saved time in their busy agendas to be here with us in this opening session. I am honoured and extremely grateful to the IAEA for inviting me to Chair this Conference.

I am standing here, welcoming you all, on behalf of the 24 international experts who have been part of the International Scientific Programme Committee of the SFM'24 Conference and who have been working hard for more than a year, under the leadership of our Scientific Secretaries, Amparo González-Espartero and Gerard Bruno, from the Department of Nuclear Energy and the Department of Nuclear Safety and Security, respectively, to set up this stage and configure a conference technical programme that we hope will be of interest to all of you. The success of this Conference required an initial effort from this whole team, and I can assure you that it has been present there at all times. The real outcome now depends on all of us present here throughout this week.

The need to combat the phenomenon of global warming, the main cause of climate change and a major, if not the biggest, current threat to the future of human life in our planet, and the changing geopolitical scene surrounding energy supply and energy security are tailwinds and the main reason why many countries are showing a renewed interest in nuclear energy as a carbon free, safe, and reliable source of energy supply for their citizens, industries and for their economic development. No matter whether the country is already a nuclear player, one-to-be or if it is in a phasing-out mode, managing spent fuel resulting from the operation of nuclear power reactors in a conscious, safe, and ethical manner is a matter of extreme importance to our societies and to the future of nuclear energy itself.

This Conference is marked up in the calendars of most of the professionals, operators, regulators, decision and policy makers and other stakeholders dealing with Spent Fuel Management since its inception back in 1998, as it allows every four years to catch up with new developments and get to know, first hand, policies and strategies of different countries, the state of the art of technologies, industrial and technical achievements, plans, ongoing projects and novelties from all around the globe. Moreover, it is of great importance for embarking countries as the management of Spent Fuel and Radioactive Waste is one of the 19 issues to be reviewed in the Integrated Nuclear Infrastructure Review services the IAEA provides to those countries.

Meeting the Moment! For those of us who do not speak English as our mother tongue, the motto of this conference may have different interpretations in our respective languages. That was also a reason why we chose it. We wanted to take a holistic approach to set the scene and create a sense of urgency in all of us to show the society that we are moving ahead, ready to face challenges and that real action is taking place in the international scene. We cannot forget that spent fuel accumulation is often viewed by many people as a societal burden and the real Achilles heel of nuclear energy.

Spent fuel is the natural byproduct of the use of nuclear fuel in nuclear power reactors and has to be safely managed from its irradiation in the reactor core to its storage, transport, recycling, and disposal, independently of the back end fuel cycle strategy selected by each country. All of these topics will be covered in this Conference throughout the week, in which we will also discuss the importance of considering all aspects of the back end of the fuel cycle for those new fuels coming from the envisaged new reactor designs in a holistic and integrated approach.

Looking backwards, it is now **almost 70 years** since the Obninsk nuclear power plant in the Soviet Union became the world's first nuclear power station generating electricity for a power grid, on June 27, 1954. Later on, Calder Hall in the United Kingdom, became the world's first full scale power station on 1956 and one year later, the Shippingport Atomic Power Station in the United States of America became the world's first full scale power station solely devoted to electricity production, which was connected to the grid in December 1957. Seven decades in which we have witnessed the evolution of all technologies involved in the different spent fuel management stages to the state of maturity we know them today. And these technologies continue evolving as a signal of a living industry which devotes a lot of human and economic resources to research and development. I hope that this conference will allow us to learn from the past, get to know recent developments and try to get a glimpse of what this spent fuel management landscape will look like in the coming years and decades, in which we expect to see deep geological repositories in operation and significant progress in advanced new technologies.

We have an intense week ahead of us, with a working **balanced** programme which has been thoroughly thought and that we all hope will fully meet your expectations. It has a great number of presentations, both in oral and poster formats, which have been grouped in seven different tracks covering the full spectrum of spent fuel management related activities, has four dedicated panel sessions (two on National Programmes, one on Innovation and Integration and another one on Stakeholder's Involvement) and has two side events (one hosted by France on the French Fuel Cycle and second one on Paving the Way for Tomorrow's SFM Workforce discussing intergenerational, gender and inclusive aspects). This venue is an excellent opportunity to learn from others, from their success and also from their failure stories. Let's work together in proving ourselves and others that we are ready to cope with these challenges.

Finally, I would like to thank all presenters for their commitment to the success of this conference, for their endeavour and dedication in preparing their papers with outstanding quality and, which is also important, in due time. Last but not least, I encourage you to become an important actor of this conference by abandoning the bystander effect, by actively participating in formal and informal interactions with your colleagues, by engaging yourselves in the discussions, by spending time in sharing your knowledge with our young generation colleagues and by approaching the representatives of the newcomer countries which will be embarking themselves in the wonders of this unique source of energy in the coming future.

Let's **meet the moment** together and rise to the occasion!

Thank you for your attention!

3. SUMMARY OF PANELS

3.1. PANEL ON NATIONAL STRATEGIES FOR SPENT FUEL MANAGEMENT (SESSIONS I AND II)

The presentation of national programmes has been a feature of this conference since its inception. It is interesting to look back to see how individual programmes have evolved with time, whether the direction has changed because of internal or external events, whether it is still on track or whether the vision remains the same but there are challenges in getting there. This learning is of value to those taking the first steps in developing a nuclear power programme or considering developing one.

Principle seven of the ten IAEA Fundamental Safety Principles states: “Radioactive waste must be managed in such a way as to avoid imposing an undue burden on future generations...” [1].

The mechanism for achieving that starts with having a national policy and an associated strategy for managing spent fuel and radioactive waste which includes a programme for delivery and a detailed plan to implement. Ten member States presented their national programmes in two sessions, I and II.

Panel on National Strategies for Spent Fuel Management – Session I comprised of six presentations, one from France, one from Japan, one from the Netherlands, one from Republic of Korea (RoK), one from the United Kingdom and one from the United States of America and it was moderated by Ms Sama Bilbao y Leon (DG-WNA).

Panel on National Strategies for Spent Fuel Management – Session II continued the presentations and discussions on national strategies, and it was comprised of four presentations, one from Hungary, one from India, one from Pakistan and one from Poland. It was moderated by Mr Hans Wanner (Hans Wanner Consulting and former President of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management).

Presenters and titles of the presentations in the two Panels are listed in Table 1 and Table 2. A summary of the main topics discussed during each Panel is included followed by the extended abstracts and papers related to the presentations.

TABLE 1. PRESENTATIONS FROM PANEL ON NATIONAL STRATEGIES FOR SPENT FUEL MANAGEMENT (Session I)

Panel moderator: Sama Bilbao y Leon (DG-WNA)		
Country	Presenter	Title
France	T. Manneville	French Strategy for Spent Fuel Management
Japan	T. Fukuda	Status of Spent Fuel Management in Japan
Netherlands	T. Klomberg	Spent Fuel and Radioactive Waste Management in the Netherlands
Korea, Republic of	H.-J. Park	Status and Prospects of the SNF Management in the Republic of Korea
United Kingdom	T. Juurmaa	Nuclear Decommissioning Authority's Strategy Development (Paper ID81)
United States of America	J. Lubinski	The National Programme in the United States of America: The Regulatory Perspective

TABLE 2. PRESENTATIONS FROM PANEL ON NATIONAL STRATEGIES FOR SPENT FUEL MANAGEMENT (Session II)

Panel moderator: Hans Wanner (Hans Wanner Consulting)		
Country	Presenter	Title
Hungary	B. Nős	Management of Spent Nuclear Fuel in Hungary
India	U. Dani	Management of Spent Nuclear Fuel in India – Experience, Challenges and Way Forward
Pakistan	M. Shoaib	National Strategy and Storage of Spent Fuel in Pakistan (Paper ID19)
Poland	B. Sośnik	Spent Fuel Management in Poland

Summary of Discussions from Panel on National Strategies for Spent Fuel Management (Session I)

This is the summary of the discussions during Session I of the Panel on National Strategies for Spent Fuel Management in the format of questions and answers, followed by the corresponding submitted papers and extended abstracts.

Q1: How do you ensure public confidence in your country? And why is public acceptance of spent fuel management important?

T. Manneville: In France, the law ensures that all national programmes and plans are monitored by an independent authority which is the national commission for public debate (Commission Nationale du Débat Public - CNDP). The CNDP reviews all programmes and decides on the level of public involvement. Major decisions such as the introduction of new EPR2 reactors, CIGEO disposal and new MOX recycling facilities have been or will be preceded by public debates.

T. Klomberg: In the Netherlands, if the public does not accept the spent fuel management plans, then there will be problems in accepting the use of nuclear energy. So, it is important to make clear to the public what are the choices with respect to spent fuel management and the reasons behind each choice. It is important that the public have all the information at hand, to make decisions based on facts and data, not just opinions.

T. Juurmaa: The mission of the NDA in the UK is not easy and at not low cost for the taxpayer. When the NDA makes big decisions, for example on our strategy, business plans, or any other topic, these are made available for public consultation with the requirement of providing responses to the questions raised. In addition, there is engagement through local stakeholder forums at all the NDA and EDF sites. It is important to have consistent messaging when communicating with the local stakeholders, and to provide accurate and underpinned information.

H.-J. Park: In RoK, reviewing the previous failures to select a DGR site, the common feature is a top down methodology from the government. The latest bill, however, is incorporating a bilateral communication with the local people. When using a stakeholder engagement plan, it is essential that local opinions are recognized. Whether the new bill is proposed by the opposition or the ruling party, communicating with each other is a common feature even if the content is somewhat different.

J. Lubinski: Engagement involves preparing for what is important today and what is coming. In looking at efficiencies and lesser requirements, this raises the question with the public whether safety is being eroded. There is communication when it comes to existing NPPs, but there is little communication on future developments. There is a need to learn from the past and adapt. Most communications from new design vendors relate to selling to the local public and communities and US NRC needs to be part of this process. Early engagement is required so regulators can be trained in the new technologies which enables appropriate response in public engagement.

Q2: What are the challenges associated with changing national policies and strategies?

H.-J. Park: Our national policy has been drastically changed by the current government. Additional change is the launching of two SMR programmes. In RoK, there are two ministries in charge of the national policy who have different views on the spent fuel management policy. One is advocating for direct disposal and the other is more in favour of recycling. The main cross cutting and common view is disposal of high level waste. So, we have to accelerate the site selection process and implementation of a DGR.

T. Klomberg: There are two challenges in the Netherlands. One is the transition to a larger nuclear programme and the second one is the introduction of new technologies. We are currently working with the different parties to establish what it means for us in terms of regulations, legislation, and practice. We have a big task ahead of us, and we are still trying to keep up with the pace of the developments.

Q3: In Japan metal casks are the preferred option for interim storing spent fuel, how was this decision made?

T. Fukuda: The preference for the use of metal casks is based upon the performance during the event at Fukushima which demonstrated that neither the primary containment nor the fuel was impacted. This has shown that metal casks are a robust system for storing spent fuel.

Q4: Regarding reprocessing and recycling, what is the logic of this approach/advice/lessons learned, and what could countries embarking on a nuclear power programme expect from this technology?

T. Manneville: The main advantages of recycling are making the most of natural resources and increasing the energy independence. In France the mono recycling of MOX fuel allows for the savings of 10% of the resources that would have been needed with an open cycle. The use of the enriched RepU could eventually lead to 10–15% more reduction. The ultimate goal in France is multiple recycling in fast reactors. In the interim, R&D has been carried out on multi recycling in PWRs, that allows potentially for 40% saving of natural resources.

T. Klomberg: In the case of the Netherlands, spent fuel from our only nuclear power plant is reprocessed and recycled, and there are a lot of advantages in doing this. Since we are dependent on other countries for several steps within the fuel cycle, it is important to ensure that the required services, e.g. reprocessing, will still be available in the future. This is more a question of infrastructure and industrial capabilities rather than policy. The difficulty mainly lies in having to plan for such a long time.

Q5: How is sustainability considered in decisions on the management of the UK's spent fuel?

T. Juurmaa: In the UK, sustainability is hardwired into our thinking. The NDA has taken a holistic view to sustainability which includes consideration of carbon emissions, environmental impacts, hazard, and risk management, impacts on socioeconomics and on the industry in general. When making a decision, options are down selected and assessed against a set of criteria which includes sustainability. We do not explicitly use the UN 17 Sustainable Development Goals (SDGs), but we have done mapping and confirmed that the criteria that we use cover the 17 SDGs. Investments are made using a business case process which looks at how we add value but also considers how we meet sustainability objectives. This is what we do at the authority level. A similar process is followed at the site level for making tactical decisions on implementation.

Q6: Regarding cooperation, it has been mentioned several times how important it is to maximize the international collaboration in the topic of waste and spent nuclear fuel. Can you outline your approach to international collaboration?

J. Lubinski: Collaboration is not just about countries or other regulators, collaboration also includes the processes. Critical paths associated with new technology deployment are focused on the front end while not as much focus is put on the back end. Some of the efforts being put into front end developments can be applied elsewhere in the nuclear fuel cycle to make processes more effective and efficient. In the USA this has been found to be the case for criticality assessment developments to support new reactor systems. The data does not necessarily transfer between countries because of different approaches/policies, but it is of value to all those working in that specific area. Regarding public confidence, we can learn from what is happening worldwide and establish dialogue with other countries on best practices to build confidence.

H.-J. Park: No country can do radioactive waste disposal by itself, and we all need to learn from one another. By collaborating, we can optimize our infrastructures, our research and development capabilities, and perhaps facilities themselves. RoK has ongoing collaboration with several countries in terms of radioactive waste disposal, for example Finland, France, and Switzerland. There are advantages in sharing technical data and the results from the underground research laboratories.

T. Manneville: The French industry already cooperates internationally in several areas including reprocessing services. As explained previously, reprocessing leads to savings in raw materials, and the reduction of the waste. So, it is important for us to give the opportunity for such advantages to other countries.

Q7: How will SMRs impact spent fuel management (SFM)?

T. Juurmaa: The UK's net zero plans include the use of SMRs, which are under development, and the fuel may be different to what we are managing today. It is important to have a credible lifecycle for these developments and as such there is a requirement in the UK to have a Funded Decommissioning Programme (FDP) where they have to develop a costed underpinned lifecycle management for their plant, for their wastes and for decommissioning. Before entering the FDP process, upfront engagement with stakeholders e.g. regulators, disposal service provider, etc, is also required. The decisions on the management of these fuels will belong to the owner of the fuels.

T. Klomberg: Looking at SMRs, the first technologies that are likely to be deployed are based on current conventional technologies, i.e. light water reactors (LWRs). From our point of view that means that their spent fuel would be possible to be reprocessed and recycled using current technologies. This provides time to think about more advanced technologies.

H.-J. Park: In RoK, we are now developing an SMR programme from both technology development and in terms of regulation. Advanced SMR technologies will lead to different SFM challenges, e.g. HALEU fuels lead to material activation problems.

J. Lubinski: There is a wide and strong operational experience for safely storing spent fuel worldwide. This will serve as the basis for storing and managing SMR spent fuels. Learning from past mistakes and looking from the standpoint of policy issues and acceptance of local communities is paramount. Another important point is that some microreactor vendors are envisaging spent fuel takeback options, where spent fuel will be managed at manufacturer site.

Q8: Twenty percent of the Netherlands is below sea level. How does this influence your DGR planning?

T. Klomberg: Not very much. In the Netherlands we have two types of geology available, one is clay, and the other is salt, both could be used to develop a DGR in the future. Netherlands has adopted a dual track strategy. We are looking into developing a DGR within the Netherlands and at the same time focused on a multinational solution. COVRA, as the waste management organization, is managing an association called ERDO, which is working together with other waste management organizations on a multinational disposal solution. This approach is supported at the ministerial level, and they are working with ministries from other countries.

Q9: What is value for money in terms of spent fuel management, and how would you measure it?

J. Lubinski: In the USA, we are not commercially recycling spent fuel. From our perspective, operators need to look at the back end to see how this comes into play and establish a cost effective process through making a business case.

T. Juurmaa: In the UK, it is about how the resources are used to generate value, therefore not just monetary. Resources include using infrastructure in the right way, wastes produced, if it generates jobs (local and wider community), etc. The NDA has a value framework which is used to evaluate the different options, with the results being published in a value framework document.

T. Manneville: In France, it is the relative value of everything when looking at the bigger picture, that does not necessarily translate into money.

Q10: How do regulatory requirements evolve within the nuclear industry?

J. Lubinski: In the case of the US NRC, we assess what is the outlook of the industry, i.e. whether it takes off due to new build or just business as usual. If business as usual, then we have to address the motivational challenge. If the industry takes off, then we need to bring in new people and skills to look at the whole cycle and for stakeholder's engagement.

Q11: Recognizing that SFM is a generational problem, how do you ensure the next generation have the right capabilities to carry on this work?

T. Klomberg: The policy in the Netherlands is no undue burden to future generations, importantly it is about minimizing the burden rather than eliminate any burden. The next generation needs to have the means (resources/know how) and money for the essential pieces of the nuclear programme. Currently, radwaste has to be transferred to COVRA and paid for, this includes supporting R&D, etc. So, they have the means. Training resources are being progressed through the Universities, technical colleges, etc.

T. Fukuda: It is difficult for us to attract university students, and we are getting less and less graduates in the field. This is not only a problem from a regulatory point of view, but also for all nuclear industry.

T. Juurmaa: The front end appears to be more attractive than the back end in the UK. Public relations have been improving their communications to install the exciting opportunities in the back end. The NDA funds R&D in Universities to sustain the knowledge base, likewise the National Laboratory also maintains the skill base.

J. Lubinski: This could be achieved through understanding the entire lifecycle, timing of it and why we are doing it, this has not been so good in the past. In the USA we are recording what the benefits are, the decisions and how we arrived at them. This will provide future generations with means to understand what was proposed and the means to be able to reevaluate them.

Key Take Away Messages from Each Panellist (Session I)

- **T. Manneville (France):** France has demonstrated that reprocessing is an efficient mechanism for minimizing the use of raw materials and managing the volume of wastes. It is already in a position to collaborate with the rest of the world in this technology.
- **T. Fukuda (Japan):** There is no reprocessing or operational BWRs in Japan currently, but same as the French in terms of recycling policy which will need to be taken on by the next generation.
- **T. Klomberg (Netherlands):** Spent fuel management is part of the whole fuel cycle and the policy makers need to recognize this.
- **H.-J. Park (Korea, Republic of):** The back end of the fuel cycle was not originally recognized in RoK. Now the front and back are closely linked. In developing SMR technology it is important to resolve the back end of the fuel cycle.
- **T. Juurmaa (United Kingdom):** The importance of learning from the past, as there are good and bad experiences. There is the need to look at the back end early in the process. For SMRs we cannot afford to miss this.
- **J. Lubinski (United States of America):** History has shown that we have been effective in managing spent fuel. Need to continue this going forward. Effective communication between all actors in the fuel cycle is important. Early dialogue with the regulator allows confidence to be installed when communicating with the public.

Moderator's Take Aways (Sama Bilbao y Leon, DG-WNA)

- The challenge of spent fuel management is not an emergency, but it is important to provide confidence to the public/stakeholders that spent fuel is being effectively managed, i.e. there is a timeline, milestones, and we are progressing against them.
- The importance of international cooperation. Working together adds value to all parties involved, sharing of infrastructures will add benefits.
- Engaging with the next generation. When communicating with the next generation it is important to show the entire picture. Yes, there is a SFM plan, and the know-how on how to manage it.

Summary of Discussions from Panel on National Strategies for Spent Fuel Management (Session II)

This is the summary of the discussions during Session II of the Panel on National Strategies for Spent Fuel Management in the format of questions and answers, followed by the corresponding submitted papers and extended abstracts.

Q1: Hungary and Pakistan have decided to wait with the decision, and to keep a flexible approach in managing the spent fuel, what are the drawbacks in delaying decisions?

B. Nős: Hungary is moving forward in the implementation of a DGR. We are now in the site selection phase which requires the estimation of the footprint of the DGR. It will be managed by considering conservative assumptions. Input data such as waste forms, packages, weights, etc. will be needed as the cross sections of tunnels, drifts and shafts will be designed based on the packages' characteristics. Again, we can make bounding assessments/assumptions, but it costs money in doing this. Keeping a flexible approach translates into cost, at some point a decision, however, will have to be made.

M. Shoaib: Only a few countries apply a closed fuel cycle policy. If Pakistan later opts for open fuel cycle then no technology challenges of closed fuel cycle will have to be addressed. Moreover, Pakistan has the option of dry fuel storage for storing SNF more than 60 years, so currently no serious drawbacks will be faced by delaying the decision. Nevertheless, if future decision is to opt for closed fuel cycle, we will have to develop working groups, set up laboratories and obtain the technology.

Q2: Question to India regarding the strategies to manage the spent fuel from thorium and fast reactors

U. Dani: In India, the national policy is a closed fuel cycle therefore research for these fuel types was started early in our institutes. In the case of fast reactors, reprocessing studies have been completed and a demonstration plant is being commissioned. Ultimately it will be an integrated facility (reprocessing, recycling material into new fuel and putting it back into the reactor). In the case of reprocessing thorium fuels, this is still under development.

Q3: No matter your strategy, everyone will need a DGR in the end. How far have you advanced in your countries with DGR and what have been the challenges so far?

B. Sośnik: In the 1990s Poland had a project to analyse the geology of the country for a possible DGR. There are possibilities in different locations, but no site selection was undertaken. This would be the next step. The funding of the DGR, which is yet to be created, will come from nuclear power plant operations. Currently, we have no further detailed steps going on.

B. Nős: Hungary undertook national screening in the early 2000s and found that only 3–5% of the country had the right geology to host a DGR. Hence, we have limited opportunity for selecting a suitable site. We started the site selection process and have established a very detailed legislative programme on how to do that. For each surface based investigation phase, we have to compile a R&D programme, which is authorized by the Hungarian Atomic Energy Authority (HAEA). Public involvement is a very important aspect in the siting, public hearing is organized as part of the licensing process. At the end of each stage, Public Limited Company for Radioactive Waste Management (PURAM) has to compile a comprehensive report on the scientific investigations and prepare a safety case, in order to identify the priorities for the next phase. Currently, we are in the first phase of site selection, and only one formation at a time is being analysed. I would like to add two things here; one challenge and one opportunity. The challenge would be the stakeholder engagement where, according to our practice local municipalities, forming an association, are kept up to date with the progresses and developments. The opportunity is the improvement of the nuclear industry. From a financing point of view, if there are more units and more nuclear power generation, obviously, the economics of scale of financing the geological disposal repository – through sharing fix costs – will improve which is usually an obstacle for small nuclear programmes.

U. Dani: In India's case, a geological survey of the country has been completed, and few candidate sites have been identified. The results have not been made public as this attracts a lot of stakeholder issues. The sites are primarily being evaluated from a technical basis. In combination with work on building costs, that has shown being related to the size of the programme, we have engaged in IAEA's programmes. So far India's DGR programme is a low scale project, however, with plans to move from 8 GW(e) towards a 100 GW(e) by 2050, this will result in more waste to be managed and more HLW. Transmutation would reduce the challenge; however, the current approach is to wait and build the DGR when there is a sizeable inventory but keeping an eye on the progress of developments at the same time.

M. Shoaib: In Pakistan the nuclear programme is relatively small with 3.5 GW(e) capacity. Spent fuel will be stored for about 60—80 years in dry storage. Efforts are being put for studying different geological formations and site selection criteria are being developed. Our approach is to collect and build up knowledge. Initial siting studies are in progress (soil sampling, etc.), and different projects in collaboration with IAEA are in place. This will allow us to be able to go forward with the development of a DGR at the appropriate time.

Q4: Poland being at an early stage of a quite ambitious nuclear power programme, do you face any challenges with human resources?

B. Sośnik: We do see a lot of issues and struggle. The project is seen as a multigenerational endeavour and requires a good people strategy to ensure we have a steady flow of educated people who are going to join the industry in Poland. Presently, it is not easy to recruit nationally, and we try to bring back people working abroad as at the end, we want to grow our own workforce, which is going to stay in Poland.

Q5: What was the reason for moving spent fuel encapsulation plant from the storage facility to the repository site in Hungary?

B. Nős: We have evaluated the siting options for the encapsulation plant and decided to relocate it. One option was to transport the spent fuel as it is in dedicated transport casks, then encapsulate it at the DGR. Because there will be different fuels to be managed and encapsulated, assessments have shown that it is better to transport different fuel types than to transport different waste packages.

Key Take Away Messages from Each Panellist (Session II)

- **M. Shoaib (Pakistan):** Every country has to explore their (energy) resources. It is important to establish R&D programmes to support decision making in managing the back end of the fuel cycle for the future generations.
- **U. Dani (India):** It is imperative to develop nuclear energy as it is the only long term solution for energy supply. Spent fuel management is key in providing confidence to the public, as people are concerned about how it is managed. I believe that the closed fuel cycle option needs to be considered as it allows resources to be maximized. However, it needs a lot of capacity building and sustained research. So, we have to work all together and contribute to make it an attractive proposition.
- **B. Nős (Hungary):** I believe we can meet the moment for nuclear industry development in three pillars. The first is storage: Providing safe storage solutions. It is on good track: safe, proven technological solutions exist. The second is flexibility: safe storage solutions provide the opportunity to keep flexibility in the back end, besides keeping flexibility, a reference scenario is needed for spent fuel management to be able to collect the necessary funding for any solution. Third pillar is the implementation of the deep geological repositories. It is emphasized, that we have to be ethical, and not to leave undue burden on future generations, so site selection or more advanced steps of implementation have to be carried out according to plans of the Member States.
- **B. Sośnik (Poland):** We all agree that developing a nuclear programme takes time. The first opportunity to develop a nuclear power programme in Poland was missed. Regardless, we have now 40 years of your experience to learn from, and we take lessons learned seriously so we will not repeat previous mistakes.

Moderator's Take Aways (Hans Wanner, Hans Wanner Consulting)

- The spent fuel management policies differ between the countries represented in this panel.
- While in some countries a decision is pending, others either plan direct disposal or strive for a closed fuel cycle by reprocessing all spent nuclear fuel.
- In all cases a deep geological repository is needed, either for spent fuel or for high level waste from reprocessing.
- Postponing the planning of such a repository until a back end policy has been decided has to be discouraged in view of the long timeframes required for that process.

FRENCH STRATEGY FOR SPENT FUEL MANAGEMENT

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Extended Abstract

Nuclear accounts for around 70% of energy production in France. There are 57 operational PWRs on 18 sites producing a total of 61.3 GW(e) of electricity. In addition to NPPs France has all the facilities necessary to support all industrial aspects of its nuclear fuel cycle. The majority of the current nuclear fuel used by French NPPs is made of enriched natural U and the corresponding SNF is reprocessed obtaining plutonium oxide, to produce MOX fuel together with depleted uranium, and reprocessed uranium (RepU) which is temporarily stored. Secondary waste from SNF reprocessing containing fission products and technological waste is stored awaiting final disposal. The MOX fuel is also used by existing French NPPs. Once spent MOX fuel is discharged from the reactor, it is stored pending future reprocessing. Finally, RepU can be enriched to produce enriched reprocessed uranium (ERU) fuel, mirroring the natural uranium fuel cycle; ERU fuel will be used by EDF in Cruas reactors, with the first charging done in 2023.

In 2022 the French president expressed his wish that six new EPR2 reactors be constructed and that studies be launched for a potential second phase corresponding to further eight EPR2s. In addition to new reactors, further announcements in 2024 have included the start of studies for a new MOX fuel manufacturing plant and a new spent fuel reprocessing plant at La Hague site. The importance of considering the nuclear fuel cycles for the latest innovative reactors in their evaluations was also highlighted.

The French National Plan for Radioactive Materials and Waste Management (Plan national de gestion des matières et des déchets radioactifs (PNGMDR)), 2022-2026, reviewed every five years, ensures that all categories of existing waste are managed properly, and that there are adequate storage facilities for the spent fuel and waste resulting from the existing fuel cycle. It also includes R&D plans for waste associated with new fuel cycles. The public, environmental and safety authorities are all consulted in the generation of the plan, in particular for the current plan before which a public debate took place.

An important difference is made in France between radioactive material and waste. Material has economic value while waste does not. In the case of waste, adequate provision needs to be made by the producer for the future management of this waste. For material, owners now need to explain how the value will be realized through valorization plans asked by the PNGMDR.

In addition to that the current PNGMDR provides a framework to keep on developing the CIGEO Deep Geological Disposal Project for the management of technical waste and fission products while keeping open options for future waste management choices.

STATUS OF SPENT FUEL MANAGEMENT IN JAPAN

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Nuclear Regulation Authority
Japan

Extended Abstract

Japan has been following the nuclear fuel cycle path. However, the startup of the nuclear fuel reprocessing plant in Aomori Rokkasho has been delayed from the original plan.

Since the Great East Japan Earthquake, Boiling Water Reactors of the same type as the one that experienced the accident have not yet been restarted and only Pressurized Water Reactors are in operation. However, the utilization rate of fuel storage pools at nuclear power plants (NPPs) in Japan remains high, and the need for interim storage has been increasing in recent years.

Tokyo Electric Power Company's (TEPCO's) Fukushima Daiichi NPP was hit by the tsunami caused by the Great East Japan Earthquake, resulting in loss of power to the plant and an accident at the NPP itself. In addition, dry storage casks were hit by the tsunami because the storage facility was located on the coast. However, no damage was caused to the casks or spent fuel stored in the cask.

Based on the aforementioned events, interim storage in metal casks is recognized as a passive and safe storage method that does not require an external power source; moreover, Nuclear Regulation Authority Japan (NRA-Japan) encourages the use of metal casks. Dual purpose casks (DPCs), used for transport and storage of spent fuel, do not require refilling during transport and thus involve low risk; moreover, NRA-Japan has introduced a type approval system to encourage the use of DPCs.

The transportability of DPCs has to be ensured after storage. This requirement was incorporated into the IAEA Transport Regulation SSR-6 (Rev. 1) as a 'shipment after storage' concept that considers the aging of transport packaging and contents. Regulations in Japan also follow this approach, requiring a design that takes aging into account.

Currently, dry storage casks are being implemented at the Tokai Daini NPP of the Japan Atomic Power Company and the Fukushima Daiichi NPP of TEPCO for spent fuel storage. In addition, an independent fuel storage facility of Recyclable-Fuel Storage Company has been established in Aomori Prefecture as an off-site storage facility, which licence has been approved by NRA-Japan and is scheduled to start operation.

The presentation discussed these regulatory approaches to spent fuel storage in Japan.

SPENT FUEL AND RADIOACTIVE WASTE MANAGEMENT IN THE NETHERLANDS

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Extended Abstract

The presentation mainly covered in short what the policy of Netherlands contains with regard to radioactive waste and what the intentions of Netherlands are in drafting an update of the Dutch National Programme for the management of radioactive waste. The National Programme has to be updated at least every ten years according to European legislation. For Netherlands, this means that an updated National Programme will be published in the course of 2025. In the National Programme the current developments in nuclear energy with regard to the incoming new government will be addressed. This new government, which is expected to be installed in summer 2024, has the ambition to realize four nuclear power plants in the Netherlands and off course this has consequences for the management of spent fuel and radioactive waste. Furthermore, in the National Programme it is the intention of Netherlands to give insight in how the path to come to a final disposal would be considered. To that end the Netherlands also tries to cooperate as much as possible with other countries to come to multinational solutions in the management of radioactive waste.

The management of spent fuel and the management of radioactive waste are closely linked. In the Netherlands the basic four principles for the management of radioactive waste also apply for spent fuel. These four principles are:

- Minimization of radioactive waste;
 - Prevent, recycle, decay, incinerate, reprocess.
- Safe management of radioactive waste, now and in the future;
 - Interim storage facility aboveground for at least 100 years;
 - Geological disposal after 100 years (2130).
- No unreasonable burden for future generations;
- Producers of radioactive waste bear the costs of waste management.

The Netherlands strives for a circular economy and wants in general to stimulate the (European) market for sustainable raw materials and the reuse of scarce materials. A specific form of reuse concerns the reprocessing of spent fuel. This also limits the generation of radioactive waste and reduces the use of raw materials. Furthermore, reprocessing of spent fuel reduces the volume and lifespan of the remaining radioactive waste.

There are in principle two destinations for spent fuel elements:

- (1) Direct storage: The spent fuel elements are stored above ground for a longer period (for example 100 years) pending a final destination. In that situation the spent fuel is addressed as radioactive waste;
- (2) Reprocessing: The still usable fissile materials (approximately 95%) are separated with the option of reuse them into nuclear fuel. The remaining, much smaller amount of highly radioactive reprocessing waste is stored for a longer period (for example 100 years) pending a final destination.

Fuel rods used in nuclear power plants can be reprocessed to recover the materials that are still usable. Reprocessing reduces the volume and lifespan of radioactive waste. The usable components of spent fuel include long lived plutonium, which ensures a very long decay time. By separating this plutonium, the radioactive waste that remains after reprocessing has a shorter lifespan.

Research shows that the choice between reprocessing and direct storage is neutral in terms of safety and non-proliferation. From an economic point of view, it depends on the specific circumstances whether reprocessing is preferable. From an environmental point of view (and in particular from the entire fuel cycle, from raw material to waste) it is more favourable to opt for reprocessing.

In contrast to highly radioactive reprocessing waste, directly stored fuel elements are not suitable for underground disposal. The highly radioactive waste from reprocessing is vitrified and packed in special canisters. This makes the waste very stable and suitable for final disposal. Spent fuel elements are not designed for final disposal and need to be conditioned.

Due to the above observations, the policy preference in the Netherlands is to reprocess spent fuel. Currently, the choice between direct storage or reprocessing of irradiated fuel in the Netherlands is left to the licence holder of a nuclear reactor. According to legislation in the Netherlands, the operator remains responsible for the safe storage of all radioactive waste during reprocessing.

To date, the spent fuel elements from the Borssele nuclear power plant are being reprocessed. The reprocessing takes place in France. There, the still usable components (95%) are separated from the fission products (radioactive waste) so that they can be reused. The radioactive waste (5%) is vitrified and sent back to the Netherlands in specific barrels and stored at COVRA.

In addition, a treaty has been concluded between France and the Netherlands, which regulates, among other things, the return of highly radioactive reprocessing waste to the Netherlands.

At the Borssele nuclear power plant, the plutonium from the reprocessed fuel rods is reused in MOX fuel rods. Enriched uranium that remains after reprocessing is used for the production of new Enriched Reprocessed Uranium (ERU) rods.

As stated, spent fuel from the nuclear power plant in the Netherlands is reprocessed and useful material is reused in new fuel rods. Most of the steps carried out in this cycle happen abroad. The current fuel cycle offers few alternative options in terms of the steps that need to be performed for recycling.

It needs to be looked into to determine to what extent the current practice of reprocessing and reuse appears can be continued in the future and what is needed to manage reprocessing in the light of the nuclear ambition of the new government in the Netherlands: a longer operating life of the Borssele nuclear power plant and the new build of four large scale new nuclear power plants. It will also be examined to what extent this is applicable to new nuclear developments such as Small Modular Reactors (SMRs). The consequences will also be mapped out if reprocessing of nuclear fuel is not an option for future management of spent fuel.

The aforementioned challenges have to be addressed as part of the decision making process when it comes to new build.

STATUS AND PROSPECTS OF THE SNF MANAGEMENT IN THE REPUBLIC OF KOREA

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Extended Abstract

The Republic of Korea's efforts in managing radioactive waste resulted in the enactment of a bill in 2005, which facilitated the siting and construction of low and intermediate level radioactive waste disposal facilities in Gyeongju. This initiative included comprehensive site investigations and public referenda to ensure transparency and public acceptance. Another significant milestone was achieved when the Institute for Korea Spent Nuclear Fuel (iKSNF) was established in 2021. The institute is co-sponsored by three governmental ministries, i.e. the Ministry of Trade, Industry and Energy (MOTIE), the Ministry of Science and ICT (MSIT), and the Nuclear Safety and Security Commission (NSSC). Its mission is to acquire core technologies of interim storage and deep geological disposal facilities for SNF, and related regulatory requirements and guidelines in spent nuclear fuel management. The iKSNF manages seven major projects and will demonstrate the results by using next programme, i.e. a generic Underground Research Laboratory (URL), and plays a key role in the field of back end nuclear fuel cycle in RoK.

The Korean government has tried to locate a SNF disposal site nine times since the 1980s. Each attempt has failed due to various reasons, recently three special bills were proposed by ruling and opposition parties in the National Assembly to resolve the situation. The common characteristics of these bills are a concrete site selection procedure and the establishment of responsible administrative governmental body, etc. to determine disposal site efficiently and definitely. The bills are still under review and was not passed until the successive 22nd National Assembly session, which started at the end of May. Another challenge is to get a budget from the Ministry of Economy and Finance to construct a generic URL, to continue the SNF disposal programme without interruption. Currently, a feasibility study is ongoing and the results are expected next year.

According to the MOTIE's basic plan for high level radioactive waste management, the ultimate goal is to operate a deep geological repository (DGR) by the end of 2050s, which can be shortened with the special bill and the generic URL preparation conditions. To do this, Republic of Korea will take a stepwise approach including: legislation; construction of a generic URL; targeted R&D. iKSNF established a performance management system for R&D achievements in April of 2024 by defining over 850 deliverables through mutual agreements between iKSNF and R&D institutes. The system ensures systematic progress and sharing outcomes among related institutes to generate synergic effects.

NUCLEAR DECOMMISSIONING AUTHORITY'S STRATEGY DEVELOPMENT (PAPER ID81)

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Abstract

The objective of the NDA's strategy for spent fuels is safe, secure, and cost effective lifecycle management. Reprocessing operations at Thorp and Magnox reprocessing plants finished in 2018 and 2022, respectively. Our strategy for managing the spent fuels that remain at the end of reprocessing focusses on three distinct phases: consolidation, safe and secure interim storage, and disposition. Our strategy development focuses on monitoring the performance of the existing storage solutions, developing bespoke solutions for some parts of the inventory, developing contingency options such as dry storage for oxide fuel as well as developing disposal options. Underpinning for the strategy development is delivered in collaboration with NDA group organizations.

1. INTRODUCTION

1.1 NDA Group

Nuclear Decommissioning Authority (NDA) is a non-departmental public body who leads the cleanup and decommissioning work at our 17 sites, including Sellafield, on behalf of the UK government. As owners of one of the largest nuclear decommissioning and remediation programmes in Europe, our main priority is to develop the strategy for how it should be carried out [1]. The NDA mission is led by the NDA and delivered by a number of different businesses carrying out a full range of activities. The NDA group is made up of the NDA and its four key component parts:

- Sellafield;
- Responsible for decommissioning the UK's most complex and challenging nuclear site.
- Nuclear Restoration Services;
- Brings together Dounreay and the sites previously branded as Magnox.
- Nuclear Waste Services;
- Work includes the programme to deliver a GDF, operation of the Low Level Repository Site and oversight of the NDA group's Integrated Waste Management Programme.
- Nuclear Transport Solutions.
- Our leading global provider of safe, secure and reliable nuclear transport solutions.

2. NDA SPENT FUELS INVENTORY

Managing the NDA's spent fuels effectively is essential to enable us to decommission and remediate our sites and release them for other uses. The inventory has a diverse range of characteristics in terms of the physical form of the fuel and the material in which it is clad. It consists of large quantities of oxide fuels, along with smaller quantities of Magnox fuel and non-standard fuel types which we refer to as 'exotic fuels'.

The oxide and Magnox spent fuels have arisen from commercial power production reactors. The spent oxide fuel that the NDA manages is predominantly Advanced Gas Cooled Reactor (AGR) spent fuel which comes to Sellafield from EDF Energy's (EDFE) seven AGR power stations in England and Scotland. The NDA is committed, through commercial contracts, to receiving and managing spent fuel from EDFE.

The Magnox reactors were the first generation of commercial nuclear power stations to operate in the UK. The NDA has the responsibility to decommission these reactors. The 26 Magnox reactors have been shut down and defuelled. Magnox reprocessing plant at Sellafield started operations in 1964 and it reprocessed 99% of Magnox fuel destined for reprocessing. In addition to Magnox fuels from commercial power stations and we own a range of metal fuels retrieved or to be retrieved from the legacy ponds. Much of this material is heavily degraded and not suitable for reprocessing in our facilities.

Our exotic fuels tend to have come from prototype, experimental or research reactors as part of the development of the nuclear power industry in the UK during the latter half of the 20th century.

More details about the NDA owned spent fuel inventory can be found in Ref. [2].

3. NDA STRATEGY FOR SPENT FUELS

Spent fuels is one of the four driving themes in NDA's strategy [1]. The objective of our strategy for our spent fuels is safe, secure, and cost effective lifecycle management. The UK Government's policy is that the decision of whether or when to reprocess spent fuel is a matter for the owner of the spent fuel [3]. Reprocessing operations at Thorp and Magnox reprocessing plants at Sellafield finished in 2018 and 2022, respectively, and there are no future plans for reprocessing of NDA owned fuels.

The strategy for managing NDA's spent fuels that remain at the end of reprocessing focusses on three distinct phases: consolidation, safe and secure interim storage, and disposition. NDA publishes a Mission progress report [5] which demonstrates the progress being made across the NDA group, and how much work there is left to do over the next 120-plus years. Progress is being reported against strategic outcomes that are aligned to the NDA's strategy. There are altogether 15 strategic outcomes related to lifecycle management of our spent fuel inventories. During the financial year 2022–2023 two of the spent fuel strategic outcomes, 'All Magnox reprocessing completed' and 'All exotic fuel reprocessing completed' were completed. The remaining outcomes are related to consolidation, storage and disposition of spent fuel inventories.

3.1. Consolidation

NDA's strategy is to consolidate all our spent fuels at Sellafield. Removing spent fuel from reactor sites and consolidating it at Sellafield significantly reduces the radioactivity and hazard at those sites and enables their decommissioning and remediation. Managing all spent fuels at Sellafield allows NDA group to make best use of the extensive and unique facilities, capabilities and expertise at this site.

Consolidation of AGR fuels from EDF's power stations to Sellafield is ongoing. There is currently ~2,500 t of AGR fuel at Sellafield and we are expecting to receive another ~2,000 t of ARG fuel from EDF before the power stations have been defuelled [2].

NDA groups are continuing to consolidate the exotic fuels from Dounreay and Harwell to Sellafield for long term management. This includes, for example, the fuels from the DFR, the PFR and the DRAGON fuel.

3.2. Safe and secure storage

NDA's strategy is that spent fuels received at Sellafield are placed into safe and secure interim storage in line with regulatory requirements. For planning purposes, we assume that spent fuels will need to be stored until a decision to dispose of them in a Geological Disposal Facility (GDF) is made and a GDF becomes available. Current plan is that a GDF will be able to receive spent fuels in 2075. These timescales are longer than the

storage time of spent fuels which have been stored in the UK prior to reprocessing, and this introduces uncertainties which will need to be managed.

NDA Group will continue to monitor performance and plant conditions and develop options, including contingency options, to manage risks and uncertainties. From a technical perspective progressing NDA's mission requires that we both understand the technical challenge that we face and have appropriate technologies and techniques to deal with it. Research, Development and Innovation (RD&I) is therefore an essential component of NDA's programme and one of the critical enablers in NDA's strategy [1].

The majority of R&D is carried out by our site licence companies and their supply chain and funded as a portion of the main budget allocation to our sites. When it comes to safe and secure storage of our spent fuels, majority of the R&D is carried out by Sellafield who are the site licensee who manages the inventory. Technical underpinning delivered by Sellafield for long term management of AGR fuels is described in more detail [7].

NDA also funds R&D directly via Direct Research Portfolio (DRP). The DRP research interests are covered in more detail in [10]. NDA's directly funded spent fuels R&D covers dry storage as a contingency option for storage of AGR fuels and alignment between spent fuel storage and disposal. Our recent progress on AGR fuel drying and dry storage options is described in [6].

3.3. Disposition

Our strategy for the spent fuels which have not been reprocessed is to place them in an interim store pending a future decision on whether to classify them as waste for disposal in a GDF. For planning purposes, we assume that the remaining spent fuels will be disposed of in a GDF and our spent fuels have been included in the inventory for geological disposal [11].

We work with Nuclear Waste Services and Sellafield on options for disposal for our spent fuel inventories. Sellafield has developed treatment concepts for some of our exotic and non-standard legacy inventories which can provide benefits for long term storage and are aligned with disposal concepts [8]. Reference [9] provides an overview of the Nuclear Waste Services scope that underpins the options for disposal of our wider spent fuel inventories.

4. DECISION MAKING

When making strategic decisions on management of our spent fuels, we consider the lifecycle of spent fuels, their products, wastes and discharges and all of the existing or potential facilities that are required to manage them. We engage with government, regulators and stakeholders on the strategic options before finalizing our strategic decisions and implementing them.

4.1. NDA value framework

The NDA mission is funded primarily by UK government and decisions taken during the delivery of our mission has to deliver value for money. In this context value for money is not about achieving the lowest cost, but rather about using resources in a way that maximizes benefits for the cost. NDA has developed Value framework [4] which includes seven factors that are valued in relation to the mission:

- Enabling the mission;
- Health and safety;
- Security;
- Environment;
- Hazard and risk reduction;
- Socio-economic impact;
- Lifetime cost.

The exact interpretation of these factors will depend on the intervention in question. More detail in application of the Value framework is provided in [4].

NDA has an obligation to consider ways in which procuring a public service might improve the economic, social and environmental well-being of the relevant area. This thinking is embedded in the Value framework. The seven value factors are can also be mapped against the UN sustainable development goals.

4.2. Magnox reprocessing

Finishing Magnox reprocessing is a recent example of a complex decision on spent fuels management where Value framework was applied. The decision making had to balance between safety of long term management of the remaining Magnox spent fuels inventory and operations at an aging asset. A decision on when to stop reprocessing was made taking into account the amount of fuel that was left, confidence in the alternative option of dry storage, the cost of continuing reprocessing, production of separated plutonium, and the condition and availability of the reprocessing plant as well as impacts on other fuels programmes and high hazard programmes.

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THE NATIONAL PROGRAMME IN THE UNITED STATES OF AMERICA: THE REGULATORY PERSPECTIVE

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Extended Abstract

The US Nuclear Regulatory Commission's (NRC) mission is to license and regulate the nation's civilian use of radioactive materials, to provide reasonable assurance of adequate protection of public health and safety, to promote the common defence and security, and to protect the environment.

In delivering this mission the vision is to demonstrate the principles of good regulation through effective, responsive, and timely regulatory actions, that are consistent with our organizational values, are open and involve a collaborative work environment.

The organization has three goals which are to: ensure the safe and secure use of radioactive materials; continue to foster a healthy organization; inspire stakeholder confidence in the NRC.

The NRC is truly independent in that it does not own, operate or promote nuclear power reactors or back end facilities. Regulation consistent approach to risk reduction, optimization.

In terms of numbers there are eighty-four licences of independent spent fuel storage facilities in thirty-six states, two licences for consolidated interim spent fuel storage facilities, and more than 3 million radioactive material packages are transported each year by road, rail, air and water. This translates into a workload of around 50—70, new, renewals or amendments, container design applications for the transport of nuclear materials and about 1000 safety inspections of fuel, reactors and material licences are performed every year.

The NRC is streamlining processes and procedures so the NRC can provide a better service to the public. This is being achieved through the application of risk evaluation tools, which are based on insights into risk potential, lessons learned, etc. Such a tool has been developed for fuel storage canisters. It enables greater flexibility in the approach to regulation, for example a recent dry cask loading was halted due to a non-compliance, applying the risk approach allowed for continuation of loading operations and resolution of the non-compliance later. The net benefit will be better use of NRC resources. This recognizes that there can be significant margins and there is little benefit in reviewing low risk application.

Stakeholder engagement is an important part of NRC processes, during this engagement the NRC should be viewed as independent, open and reliable. It has two objectives for inspiring stakeholder confidence these are to: uphold an NRC decision making process that is data driven and evidence based while ensuring information is available and accessible to interested stakeholders; engage stakeholders in NRC activities in an effective and transparent manner. The objectives are being delivered through developing effective communication strategies whereby stakeholders are engaged in a fair and timely manner to ensure they are aware and understand developments, including providing timely feedback.

In going forward the NRC is looking to be adaptable to change through keeping up to pace with new technologies, build on inspiring stakeholder confidence and applying its risk informed approach to regulation.

There is evidence of greater attention being given to impacts of fuel cycle on disposal and vice versa, but there is a need for urgency on work to understand optimization of the whole back end and to actively implement these strategies on the ground.

MANAGEMENT OF SPENT NUCLEAR FUEL IN HUNGARY

B. NÓŠ

Public Limited Company for Radioactive Waste Management (PURAM)

Hungary

Extended Abstract

In Hungary, spent fuel is generated in three facilities: at the Paks NPP (four WWER-440 units), at the Budapest Research Reactor and at the Training Reactor of the Budapest University of Technology and Economics. The decision has been made to construct two new WWER-1200 units at the Paks site (Paks II), which could be operational by the early 2030s.

A final decision has not yet been made regarding the back end of the nuclear fuel cycle for power reactors. The direct disposal of spent nuclear fuel (open fuel cycle) is considered to be a reference scenario, serving as a basis for the cost calculations.

After few years of cooling in the decay pools of Paks NPP, the spent fuel is transferred to the Spent Fuel Interim Storage Facility (SFISF), which is adjacent to the NPP site. The licensee of the SFISF is Public Limited Company for Radioactive Waste Management (PURAM), the waste management organization of Hungary.

According to the National Policy, the final disposal of spent fuel and other high level radioactive wastes has to be done in Hungary, in a geological disposal facility (GDF). A multistage site selection programme is ongoing with the aim to find the suitable area, which can host the GDF.

The policy for the management of spent fuel, generated in the Research and the Training reactor is the repatriation of the spent fuel to the manufacturer's country. The Training reactor is operated with the original core, and spent fuel from the Research Reactor is stored on site in pool.

Integrated spent fuel storage – a holistic solution

The original lifetime of Paks NPP was 30 years, which was prolonged with additional 20 years, so the operational licence of the units expires between 2032-2037. Recently the Hungarian Parliament took note of the subsequent lifetime prolongation of the units of Paks NPP. The utility initiated a project for the preparation of the necessary technical justifications and licensing documentations proving additional 20 years lifetime prolongation.

Based on the Law on Atomic Energy in Hungary, before issuing the licence of commissioning a new NPP or for the lifetime prolongation of existing units, it has to be demonstrated that the generated spent nuclear fuel can be safely stored. Therefore, PURAM started to identify the potential solutions for storage. The aim is to find synergies and select a holistic solution taking into account the Hungarian boundary conditions. The scope of the task was defined to provide solution for:

- Spent fuel generated from the 70 years of operation of Paks NPP;
- Spent fuel generated from Paks II units;
- Spent fuel generated from the Training and Research Reactor (alternatively to repatriation).

The current SFISF for Paks NPP spent fuel is a modular vault dry storage system (MVDS). The facility has a licence for constructing 33 vaults, which can provide enough storage capacity for spent fuel generated from 50 years of operation of Paks NPP. As part of the project, different storage concepts – having WWER-440 reference – were screened. From technical point of view, the most limiting parameter is the thermal capacity of the casks and other storage systems, because Paks NPP has limited storage capacity in the decay pools, so the storage time is limited there. On the other hand, because of the fuel developments, the initial enrichment and the final average burnup of the spent fuel has increased, resulting in higher thermal power of the spent fuel

assemblies. Taking into account the Hungarian specificities, three alternative storage options are considered (HI-STORM, CASTOR 440/84M, SKODA 440/84M). For storing Paks II spent fuel, TUK 137 T.E cask type, and for the Research- and Training Reactor fuel, SKODA VPVR/M are taken into account in the conceptual plan.

The preferred route for transferring the spent fuel from Paks II is railway transport. The advantage of using cask type storage for Paks NPP spent fuel from subsequent lifetime prolongation is that in that way the railway connection can be provided for Paks II as well. The conceptual design considers all storage solutions on the same site, where the MVDS facility is located. This results in an optimized operational cost for the long term, because for example the monitoring, physical protection and infrastructures can be shared by the different facility parts.

Encapsulation of spent fuel is necessary before final disposal. In the previous conceptual design, the encapsulation plant was considered at the SFISF site. Because spent fuel with different geometry (WWER-440 and WWER-1200) has to be encapsulated, in the updated conceptual design the encapsulation plant is relocated to the GDF site.

Flexible and ethical back end policy

In Hungary, because of the new built programme, the nuclear based energy production will last until almost to the end of this century. This extremely long timeframe provides the opportunity for the development of advanced solutions for the closure of the nuclear fuel cycle. Therefore, the flexibility in the back end is important, to be able to consider these advancements and evaluate those within the Hungarian boundary conditions.

On the other hand, it is an ethical requirement not to leave undue burden to future generations. So, it is an obligation to take care of the residual wastes from any type of nuclear fuel cycle option, including the endpoint: disposal. Any back end solution may result some high level and/or long lived radioactive waste, which can be safely disposed of in a GDF.

Based on the previously mentioned preconditions, the policy concerning the back end of the nuclear fuel cycle in Hungary follows the ‘do and see’ principle, meaning that the open cycle, i.e. direct, domestic disposal of spent fuel originating from nuclear power plants has been determined as the reference scenario, which provides the basis of the relevant cost estimates. Domestic and international developments concerning the back end of the fuel cycle have to be followed (‘see’) and if necessary, need to be incorporated into the policy, while at the same time progress has to be made on the site selection of the domestic GDF (‘do’).

A decision making roadmap has been developed and the different aspects have been determined, which has to be considered for the regular review of the back end policy. This has to be made every time, when the National Policy and the National Programme is updated, based on the Law on Atomic Energy at least every five years.

MANAGEMENT OF SPENT NUCLEAR FUEL IN INDIA – EXPERIENCE, CHALLENGES AND WAY FORWARD

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Extended Abstract

Global warming and climate change are phenomena that affect people and countries all around the world. To protect the future and present generations, immediate steps for net zero emissions and a cleaner environment are necessary. Prime Minister of India Shri Narendra Modi announced the target to achieve net zero by 2070 at the 26th session of the United Nations Framework Convention on Climate Change (COP 26) in November 2021. This necessitates ‘Long term low-carbon development strategy’ which depends on seven key transitions including low carbon development of electricity systems consistent with development [1]. Dr Jitendra Singh, Union Minister of State (Independent Charge) Science and Technology; Minister of State in the Prime Minister’s Office, space and atomic energy, said “India’s energy mix strategies include a larger shift toward clean energy alternatives, increased manufacturing capacities, energy use efficiency and a policy push for Hydrogen...” [2]. As a clean energy alternative, nuclear energy is committed to play a crucial role in satisfying the growing need of electricity along with expansion of electricity production capacity based on renewable energy sources like solar, wind etc.

Nuclear power programme

At present, 24 nuclear power reactors with an installed capacity of 8180 MW(e) are under operation in India. Besides this, eight reactors with total capacity of 6800 MW(e) are under construction. In addition, preparatory activities for ten 700 MW(e) PHWRs in fleet mode, having administrative approval and financial sanction of the Government of India, are in various stages of process. With progressive completion of all the above project units, the total installed capacity of nuclear power plants is envisaged to reach 21980 MW(e) by 2031–32. The nuclear power capacity will be further expanded to realize the commitment towards cleaner environment with sustained development of country.

India has unique position with respect to nuclear fuel resources involving limited sources of uranium but large depositions of thorium in country. To extract large energy from available resource of nuclear fuel for long term energy solution, tapping of energy from thorium has also been considered necessary besides that from uranium and three stage nuclear power programme was articulated by Dr. Homi J. Bhabha, the founder of nuclear energy programme in India. Natural uranium is utilized as fuel in Pressurized Heavy Water Reactor (PHWR) at first stage to produce electricity as well as Plutonium, which can be utilized as Mixed Oxide (MOX) fuel in Fast Breeder Reactor (FBR) in second stage to generate the energy and also enable to breed the uranium-233 (^{233}U) from thorium. In third stage, $^{232}\text{Th} - ^{233}\text{U}$ is planned to be used as fuel in advanced reactors for energy production from large resource of thorium to achieve long term energy security [3, 4, 5].

While natural uranium based commercial PHWRs, candidate reactors for first stage, are under operation, Fast Breeder Test Reactor (FBTR) is also under operation more than three decades for research in the field of fast neutron spectrum as well as gaining experience for fast neutron reactor fuel cycle. First commercial sodium cooled Prototype Fast Breeder Reactor (PFBR) having Mixed Oxide (MOX) fuel is under commissioning.

Legal framework and regulation

Atomic Energy Act, 1962, and Rules promulgated thereunder provide for a legal and regulatory framework for control over nuclear fuel cycle facilities and activities with defined roles and responsibilities. The independent regulatory bodies ensure the safety and security of each stage of life cycle of fuel cycle facilities including site selection, design and construction, commissioning, regular operation as well as dismantling and decommissioning. Such framework and regulation ensure the safety and security of facilities as well as

radioactive material at all stage. As a result, excellent track record from nuclear safety and security could be seen during operation of fuel cycle facilities for more than six decades in country.

Strategy for managing spent nuclear fuel

Realization of three stage nuclear power programme requires closing the fuel cycle by reprocessing of spent fuel at each stage for recovery of nuclear materials to recycle back in reactors. India is committed to the closed fuel cycle and perceives the spent fuel as useful source of energy. The recovered plutonium from PHWR spent fuel reprocessing is to be utilized in sodium cooled fast breeder reactors along with recovered uranium as MOX fuel in multirecycling concept enabling maximum utilization of fuel for electricity generation (Fig. 1). This strategy not only enables recycling of fissile and fertile elements into the nuclear reactor, but also presents us with an opportunity to reduce the radiotoxicity of the final waste for disposal. The High Level Waste (HLW) generated from reprocessing of spent nuclear fuel is immobilized in inert matrix and interim stored in air cooled vault prior to disposal in Deep Geological Repository (DGR). Developmental activities carried out in the recent timeline have helped in the evolution of the partition strategy that not only helps to reduce the radiotoxicity of the high level waste but also helps in separation of useful radionuclides for societal benefits [6].

Currently, 24 nuclear power reactors, comprising of PHWRs as well as LWRs, are under operation for generation of electricity in India. All the activities of back end of fuel cycle involving storage, transport and reprocessing of spent nuclear fuel as well as management of high level waste are performed with utmost care imparting highest level of safety and security for safe management of spent nuclear fuel. Same can be observed from excellent track record of practices of these activities for about five decades. The spent nuclear fuel, coming out from nuclear reactors, is stored in wet storage facilities, comprising of spent fuel storage ponds, for ensuring safe removal of decay heat as well as adequate shielding. Presently, spent nuclear fuels from PHWRs are taken up for reprocessing while those from LWRs are continued safe storage in wet storage system.

The spent nuclear fuels of PHWRs are transported to reprocessing site abiding the guidelines and regulations imparted by regulator ensuring its safety as well as security. The casks that carry spent fuel during transport are appropriately designed to not only provide the necessary shielding at all times during transport but are also designed to remain intact during off-normal situations including impact, fire, etc.

Two sites, Tarapur and Kalpakkam, have reprocessing facilities for spent nuclear fuel from PHWRs. This spent fuel is reprocessed using PUREX based aqueous reprocessing process. The challenging activities with regard to spent fuel handling, head end operations, dissolution, solvent extraction cycles and final conversions are all carried out in conformity with internationally laid out safety regulations. Automated charging facility and gang chopper are few examples of improvement of head end system to overcome the bottlenecking of capacity as well as reduction of manual intervention besides the numerous improvements in process for obtaining better product recovery, quality as well as safety of facility. Periodic surveillance and inspection of safety related system are carried out for ensuring safe operation of facilities. Aged equipment and systems are replaced at regular interval, after adequate decontamination, for ensuring the availability of facilities for operation at desire capacity.

The recovered products are utilized for fabrication of MOX fuel for fast reactor programme. The fabrication of fuel pins with MOX fuel of desire quality is ensured utilizing the specially designed glove box based fuel fabrication facility at Tarapur.

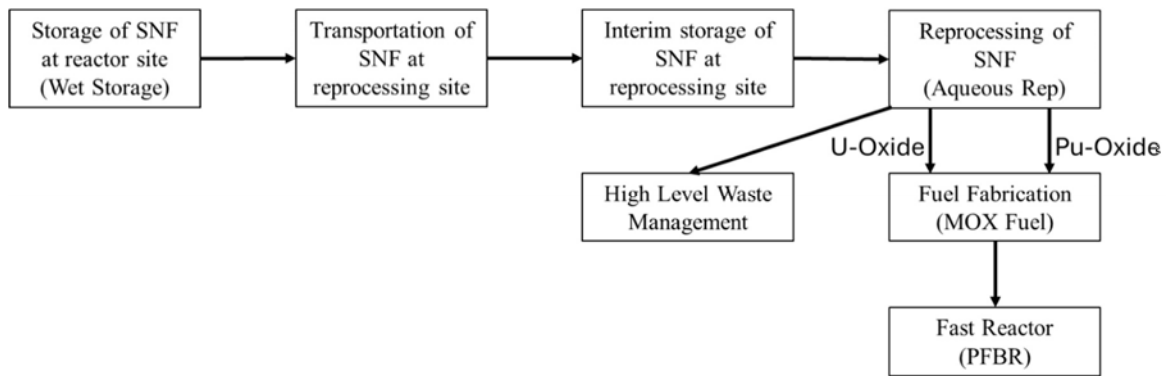


FIG. 1. Strategy of PHWR spent nuclear fuel.

Reprocessing of PHWR spent nuclear fuel is matured technology with experience of more than five decades. Such indigenous, industrially matured technology is being now extended to set up an integrated nuclear recycle project with a name plate capacity of 600 tHM/year. Such large capacity plant is aimed to meet the need of expanding nuclear power programme of country. The plant will comprise of the back end fuel facilities like reprocessing, waste management as well as fuel fabrication facilities (for recycling fuel) with spent fuel as feed and fabricated fuel as well as vitrified waste canisters as output.

In addition to reprocessing of PHWR spent nuclear fuel, the technology demonstration for reprocessing of FBTR spent nuclear fuel is also carried out at Kalpakkam. Recently, Demonstration Fast Reactor Fuel Reprocessing Plant (DFRP), a precursor to large scale plants for fast reactor spent nuclear fuel reprocessing, has been inaugurated by Honorable Prime Minister Shri Narendra Modi [7]. Higher amount of fissile materials, higher burnup of fuel, lesser cooling period, higher concentration of fission product are challenges for reprocessing fast reactor spent nuclear fuel in comparison to those from PHWRs. Aqueous reprocessing flow sheet with improved processing steps and equipment is developed for reprocessing of fast reactor spent nuclear fuel. Based on same, a large scale Fast Reactor Fuel Cycle Facility (FRFCF) comprising of reprocessing facility, waste management facility and fuel fabrication facility is under construction at Kalpakkam site for reprocessing of PFBR spent nuclear fuel.

Treatment of High Level Waste (HLW)

Safe and effective management of High Level Liquid Waste (HLLW), generated during reprocessing of SNF, is an important and decisive aspect for selection of closed fuel cycle. HLLW contains more than 99% of radioactivity present in SNF. Conventionally, HLLW is immobilized in inert glass matrix by vitrification process to immobilize and isolate the radionuclides from the environment. Vitrified HLLW is stored in passive air cooled vault for removal of decay heat for few decades and then planned to be disposed of in a DGR, likely to be built in stable granitic host rock below ground at about eight hundred meter depth.

Vitrification facility is co-located with the reprocessing facility at Tarapur as well as Kalpakkam site. Joule Heated Ceramic Melter (JHCM) based vitrification systems are deployed for immobilization of HLLW at Tarapur as well as Kalpakkam site. A new vitrification facility AVS-Annex has been constructed at Tarapur. This facility is likely to be commissioned by the end of 2024. The key feature of this facility is that it will demonstrate the 'Roll-in Roll-out' concept of melter to take care of limited life of JHCM. Cold Crucible Induction Melter (CCIM) is also developed and demonstrated with inactive trials for vitrification of HLLW. Both the melters (JHCM and CCIM) are under installation in Waste Immobilisation Plant at Kalpakkam site after obtaining necessary regulatory clearances. Each site has an interim storage facility for storage of vitrified waste canisters.

Partitioning of HLLW

Development activities are focused on partitioning of HLLW with objective of minimizing the waste volume for final disposal at DGR. Besides waste volume minimization, it also opens the opportunity for recovery of

valuable radionuclide for societal application as well as way for transmutation of minor actinides. The first industrial experience in setting up and operation of a completely indigenous Actinide Partitioning Demonstration Facility (ASDF) at Tarapur in the year 2013 has paved the way for this strategy to be inducted into our back end plants [8, 9]. The second such facility was set up and commissioned in 2015 at Trombay, which has not only led to separation of radionuclides from the inactive content of HLLW but has also made it possible for the use of few of the radionuclides for societal applications. Important among them are ^{137}Cs , which is separated and converted to glass rods for its use as blood irradiators and ^{90}Sr , which is purified further and milked for ^{90}Y , which is being used for therapeutic application as ^{90}Y -acetate. ^{106}Ru separated from waste has also been used for preparation of eye plaques for eye cancer treatment with very positive feedback.

One of the key parameters for successful partitioning of HLLW is the development and bulk synthesis of tailor-made ligands for selective/group separation of radionuclides from HLLW. Such ligands are indigenously developed to meet the requirement of various stages of partitioning technology for separation of radionuclides from HLLW. The competency in bulk synthesis of these ligands were also achieved to meet the desire requirement for engineering scale applications.

The continuous R&D in management of HLLW and operation of these facilities has strengthened our knowledge base and imparted useful experience to us. Technologies for partitioning of HLLW and separation of useful radionuclides will be deployed in Waste Immobilisation Plant at Kalpakkam and other new plants in future.

Dismantling and decommissioning of aged system

The aged systems of fuel cycle facilities, after completion of useful life for operation, require a special attention with respect to decontamination and decommissioning to avoid the long term liability. To gain experience and expertise, the process systems installed inside the hot cells of an old high level waste management facility in Waste Immobilisation Plant at Tarapur site were dismantled remotely. Based on the healthy conditions of the civil structure of the facility, the precious hot cell will be made available for further utilization of fuel cycle activities.

Deep Geological Repository

The waste packages containing long lived radionuclides, such as vitrified high level waste canisters, have to be disposed of in a Deep Geological Repository (DGR). Considering the generation of less amount of high level waste, mainly due to adoption of closed fuel cycle and development of partitioning based HLW management strategy, necessity of DGR in country is not envisaged in near future. However, design and development work in the field of DGR is continuing with respect to identification of desire quality of host media, characterization of host media, selection and characterization of back fill material, conceptual design and layout of repository, thermo-mechanic studies, etc.

Conclusion

Nuclear energy is considered as viable alternative resource to meet the target of 'net zero emission' by 2070 and expansion of nuclear power programme is under way. The indigenous Indian technology based three stage nuclear power programme will be key while development and expansion of nuclear power programme. India is committed to the closed fuel cycle and perceives the spent fuel as useful source of energy. As far as reprocessing of PHWR spent fuel is considered, the technology maturity is achieved and large scale plant is being setting up to expand reprocessing capacities. Reprocessing flowsheet for fast reactor spent fuel is demonstrated and large scale reprocessing plant is under construction. HLW from reprocessing of spent nuclear fuel is safely managed by vitrification in a glass matrix followed by interim storage in air cooled vaults. Partitioning technologies are demonstrated for HLW with objective to waste volume minimization as well as recovery of valuable radionuclides for societal application as off-shoot application.

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NATIONAL STRATEGY AND STORAGE OF SPENT FUEL IN PAKISTAN

(Paper ID19)

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Abstract

National strategy on safe management of spent fuel in Pakistan is briefly described including the role of relevant stakeholders. Six nuclear power reactors are operational at two different sites: CNPGS (Chashma Nuclear Power Generating Station) and KNPGS (Karachi Nuclear Power Generating Station). Out of these six reactors, four are operating in Chashma and two are operating in Karachi. One reactor is under construction phase at Chashma. CNPGS: Status of total spent fuel storage at four different plants is described and wet storage at CNPGS is discussed. Further, long term storage strategy (dry storage is described) including a brief description of canisters, transfer cask, storage building, etc. Capacity of dry storage is also narrated. Licensing issues are also discussed. KNPGS: Spent Fuel Bay is discussed. It is mainly divided into four parts i.e. storage area, inspection area, shipping cask area and decontamination area. Capacity of wet storage and details of water shielding height is described. Analysis of bay cooling capacity, criticality and seismic activity as well as high density tray rack (HDTR) are also discussed. KANUPP Spent Fuel Dry Storage (KSFDS) is described as well as post Fukushima policies and initiatives.

1. PAKISTAN'S NUCLEAR POWER PROGRAMME

In Pakistan, SNF is generated from operation of Nuclear Power Plants (NPPs) and research reactors. At Karachi site, one Pressurized Heavy Water Reactor (PHWR) (KANUPP-1) having rated capacity of ~125 MW(e) has been permanently shut down since 2021. Two Pressurized Water Reactors (PWRs) KANUPP-2 and KANUPP-3 having Gross Capacity of 1100 MW(e) each are operational at Karachi site [1]. Currently, at Chashma Nuclear Power Generating Station (CNPGS), four Pressurized Water Reactors (PWRs) Chashma Nuclear Power Plants, CHASNUPP-1, 2, 3 and 4, having Gross Capacities of 325, 325, 340 and 340 MW(e) respectively, are in operation since 2000, 2011, 2016 and 2017 [1]. Total Nuclear Power Generation from six NPP's accounts to be ~ 3530 MW(e). The generation of SNF will increase manifold as NPPs continue operating and more power plants are added to meet national energy requirement.

2. NATIONAL POLICY AND STRATEGY

Pakistan Nuclear Regulatory Authority (PNRA) published its "National Policy on Safe Management of Radioactive Waste, Decommissioning and Spent Nuclear Fuel in Islamic Republic of Pakistan (RWP-01/2018)" in 2018 [2]. Current Policy states that Nuclear Power Reactor's spent fuel is a valued entity and that "spent nuclear fuel is kept at licensed nuclear facilities and verdict regarding the destiny of spent fuel will be made timely by Government of Pakistan" [2]. Policy also entrusts Pakistan Atomic Energy Commission as a sole responsible for safe and secure management of spent nuclear fuel [2].

To achieve the objectives laid down in the policy, National Strategy on Safe Management of Spent Nuclear Fuel (SNF) in Pakistan has been formulated by Pakistan Atomic Energy Commission [3]. This plan suggests a top level outline of options to guarantee the safe and environmentally satisfactory management of SNF. Until Government's decision, the SNF has to be managed in a safe, responsible, and effective way, without imposing undue burden on future generations. This will be done by initially storing the SNF in water filled storage pools and thereafter in dry storage systems. Both wet and dry SNF storage have to be carried out in licensed facilities.

Later on, depending upon Government decision, if open fuel cycle is opted then it is a requirement that the SNF is conditioned/encapsulated in purpose designed disposal canisters for final disposal in a DGR. The repository will be located underground in a stable geological formation to provide long term containment and isolation of the waste from the accessible biosphere. If closed fuel cycle is opted, then the SNF has to be reprocessed in order to recover the energetic components, i.e. the plutonium and the uranium. The

recovered/separated energetic components has to be used to fabricate fuel for thermal reactors. The resulting HLW from reprocessing will be conditioned for deep geological disposal. Research is needed and will be conducted to reduce the proportion of long lived radioisotopes present in HLW through the Partitioning and Transmutation (P&T) processes.

2.1. Stakeholders Responsibilities

2.1.1. Generators

Generators of SNF are responsible for the technical, financial, and administrative management including treatment, conditioning, dry storage, safety assessment and on-site transportation of SNF. All these activities need to be carried out in accordance with national regulatory requirements and IAEA safeguards.

2.1.2. Disposal Facility Operator

The disposal facility operator are responsible for the safe disposal of SNF/HLW in a DGR. The operator has to take all the essential actions for site selection and characterization, safety assessment, design, construction, operation, closing and, if required, supervision after closing, in compliance with the regulatory requirements.

2.1.3. Regulator

The regulatory body is required to establish the regulatory requirements for all the steps associated with the management of SNF. To meet the requirements for the various stages of the licensing process the regulator needs to set out the procedures and required conditions. Moreover, the regulator has to carry out activities which are necessary to ensure that the conditions are met.

3. SPENT FUEL MANAGEMENT AT CNPGS

Currently, at Chashma Nuclear Power Generating Station (CNPGS), four Pressurized Water Reactors (PWRs), Chashma Nuclear Power Plants, C1, C2, C3 and C4, having Gross Capacity of 1330 MW(e) are in operation. Detail of SNF storage is as below:

3.1. Wet storage at CNPGS

Wet storage has been effectively in use for many years and is a mature technology. Designs are progressing to enhance the levels of passive safety and resistance to outer and malicious actions. Wet storage offers easier surveillance of fuel status and larger tractability in post-storage movement and packaging.

Following characteristics are associated with wet storage:

- (i) No mobility of spent fuel;
- (ii) Forced cooling is required for spent fuel;
- (iii) Purification system is necessary;
- (iv) Leakages are hard to repair;
- (v) In case of accident all inventory of SNF is present at the pool;
- (vi) Waste generation is a permanent feature.

3.1.1. Status of Spent Fuel at CNPGS

Capacity of C1 spent fuel pool was going to finish by 2021 so additional storage capacity of C1 was provided by shifting some storage racks from C3 to C1 pool area. Current status of spent nuclear fuel at four different plants of CNPGS is shown in Table 1.

TABLE 1. STATUS OF SNF STORAGE AT CNPGS BY FEBRUARY 2024

Plant	Storage Capacity*	Occupied*	Remaining Capacity*	Adequacy (Year)
C1	912 FA	640 FA	272 FA	2028
C2	741 FA	360 FA	381 FA	2031
C3	570 FA	200 FA	370 FA	2032
C4	741 FA	160 FA	581 FA	2037

*FA: Fuel Assembly

3.2. PWR Dry Storage at CNPGS

CNPGS has decided to establish a dry storage facility which will serve as long term storage for spent fuel until availability of spent fuel disposal or recycling facility (Wait-and-See). Currently that facility is in development phase and is planned to be operational by the end of 2025.

3.2.1. Features of Dry Storage

The cask dry storage system will provide confinement, radiation shielding, structural integrity, criticality control, and heat removal for SNF. Due to extreme environmental conditions and security issues, indoor storage of dry casks on concrete flooring is chosen. Construction of three buildings of size 150m x 20m with passive ventilation features will be started, with a total capacity of 375 dry casks which will be sufficient enough to store SNF generated from 60 years of operation of C1 – C4. The main features of the cask dry storage system are:

- Canister (including basket);
- One Metallic Cask (Transfer Cask): Weight 60 tonnes;
- Bogie²: Load bearing capacity is 200 tonnes;
- Single purpose Concrete Casks (dry storage): Weight 80 tonnes;
- Storage building with hot cell.

Fuel cooled for minimum of 10 years will be transferred to cask loading pool. Fuel will be loaded in canisters already placed in transfer cask. After loading, plug of canister will be bolted and water left in canisters will be extracted out of canisters. Meanwhile helium blanket will be made available in canisters environment. After careful inspection, plug of transfer cask will be placed. Transfer cask will be monitored and decontaminated if required to achieve/meet acceptable criteria. Transfer cask will be transferred to PWR dry storage and placed on a bogie. This bogie has a load bearing capacity of 200 tonnes. Transfer cask will be shifted to a hot cell where spent fuel placed in a canister will be transferred from transfer cask to a dry storage cask.

3.2.2. Licensing of Dry Storage

For site specific licence of dry storage facility, CNPGS will follow USNRC 10 CFR 72 [4]. Guidelines for licensing process will be followed from, PNRA regulation “Regulations for Licensing of Nuclear Installations in Pakistan, PAK/909 (Rev.1)” [5]. Letter of intent and application for licence has been forwarded to PNRA. CNPGS request for provision of safeguards measures has been proceeded from Directorate of Disarmament and Safeguard of PAEC to the IAEA.

4. SPENT FUEL MANAGEMENT AT KNP GS

At Karachi site, one Pressurized Heavy Water Reactor (PHWR) (KANUPP-1) having rated capacity of ~125 MW(e) started its commercial operation in 1972 and completed 30 years of operation in 2012. By

² As used in this paper the term bogie refers to the entire transporter.

refurbishment and safety upgrades, KANUPP operational life was extended for additional 8 years. Plant was put on permanent shut down in 2021.

4.1. Spent fuel bay of KANUPP

The spent fuel bay of KANUPP comprised four areas: Storage area, Inspection area, Shipping cask area, and Decontamination area. The main characteristics of the spent fuel bay are:

- (i) Each storage tray contains eleven bundles of spent fuel,
- (ii) Design Storage Plan: 120 piles of trays each having 18 tiers of trays,
- (iii) Design capacity: 23 760 bundles of spent fuel,
- (iv) Total Depth of water: 5.94 m,
- (v) Thickness of Water Shield: 3.96 m,
- (vi) Dose rate at 1 foot above the water surface is 8.7×10^{-3} mSv/h.

Spent fuel bay was designed for 20 years of operation with 80% capacity factor. KANUPP spent fuel storage bay reached its design capacity in June 2010.

4.2. Enhancement in storage capacity of spent fuel bay

Storage capacity of SNF in KANUPP was filled in 2010. A dry storage facility was planned as a long term solution to increase storage capacity, but an alternate short term remedy was to enhance the storage capacity of existing spent fuel bay.

4.2.1. Analysis Performed Prior to Enhancing Storage Capacity

For enhancement in storage capacity following rigorous assessment and analysis were performed:

- (i) **Computation of thickness of water column for shielding:** Fuel when stacked in 24 fuel trays has active height of about 2.44 m and the water column available for shielding of spent fuel is 3.51 m against design water column thickness of 2.13 m. Dose rate at 3.51 m water column comes out as 2.8×10^{-6} mSv/h,
- (ii) **Analysis of cooling capacity of bay water:** Total cooling capacity of bay cooling system is 1.8 MW(th). Heat generated in the spent fuel storage bay due to overall 31 680 spent fuel bundles is 0.21 MW(th). It can be considered that the design is quite safe,
- (iii) **Criticality assessment:** Spent fuel bay analysis of operational and accidental conditions reveals that in high density tray rack (HDTR) proposed layout, spent fuel will remain sub-critical. K_{eff} is reduced more by use of steel in spent fuel tray, racks and liner in nearby walls of bay,
- (iv) **Seismic Analysis:** Seismic analysis helped to evaluate the firmness against seismic activity (ground acceleration 0.2 g). Analysis shows that overturning will not occur under the specific seismic activity. Sliding will occur, however quite less than the clearance available between two side by side racks or between a rack and bay wall. Axial, bending, and shear stresses are within the permissible limits during stress analysis.

4.2.2. Salient Features of Enhanced Storage

Storage capacity of spent fuel bay was enhanced by increasing tray stack height from 18 layers to 24 by employing indigenously designed, manufactured, and tested (HDTR). Two columns each consisting of 24 layers of trays were loaded into one rack. Each HDTR placement in bay enhances about 1.5 month's storage capacity. Each HDTR has the storage capacity of 528 spent fuel bundles, resulting in overall enhancement of storage capacity from 23 760 to 31 680 spent fuel bundles. Implementation of HDTR System at KANUPP has enhanced about 1/3rd of design storage capacity. Design was approved by PNRA and the IAEA and it is

capable to incorporate the IAEA safeguard seals. Total inventory of spent fuel bundles by February 2024 is 31 000 in spent fuel bay.

4.3. KANUPP Spent Fuel Dry Storage (KSFDS)

To solve future spent fuel storage problem, KANUPP Spent Fuel Dry Storage (KSFDS) facility was constructed and became operational in 2019. This facility can store spent fuel for approx. 50 years until the Deep Geological Repository or recycling facility, if policy decision takes place, are available. This is the facility for the interim storage of the spent fuel generated from the existing/future planned Nuclear Power Plants.

Whole process of loading of spent fuel in the basket and basket in the cask is carried out underwater in the spent fuel bay. 54 spent fuel bundles are placed in the austenitic stainless steel basket in vertical position. Two steel baskets are loaded in the storage cask. Total 108 spent fuel bundles are stored in each storage cask. The storage cask after complete decontamination, clamping of top lid with bolts and welding of drain port, is transported to the dry storage facility. Spent fuel can be shifted to dry storage after minimum storage of 10 years in wet storage to reduce decay heat to such a reasonable level that fuel can be stored in dry cask without any forced cooling. Design of dry cask is based on passive cooling only. 336 storage casks can be stored in the facility. Total inventory of spent fuel by February 2024 is 3672 spent fuel assemblies stored in 34 storage casks.

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SPENT FUEL MANAGEMENT IN POLAND

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Extended Abstract

Poland already investigated developing a nuclear power programme in the 1980s with the intention to build four VVER-440 units. The project was paused in the late 1980s, as just very recently relatively cheap coal plants were commissioned, which together with a collapse of the Polish economy, lead to reduced energy consumption and low energy prices. Due to these reasons and a local public referendum not supporting further nuclear power development, the project was finally cancelled in the early 1990s.

The original construction site still exists, and the reactor footprints can still be seen. Despite not pursuing the nuclear power generation anymore, the country still has a National Atomic Energy Agency, Radioactive Waste Disposal Facility, National Centre for Nuclear Research (incl. research reactors) and other research institutions.

Apart from PEJ and the Westinghouse AP1000, there are several other projects in Poland developing power reactor technologies, like the KHNP and various SMRs. These different programmes need to work together on issues such as DGR/waste management.

The Polish radioactive waste plan that was established in 2020 has a deep geological repository as the final step. The fuel cycle itself is not restricted, i.e. the operator can choose to treat spent fuel as resource or waste, depending on economical assessment. Such an assessment has been done and as for today, spent fuel disposal has been declared the preferred solution over. The fuel cycle choice will be reassessed after the first reactor going online. Likewise, there is no directive in terms of the choice of spent fuel storage location nor technology, therefore it is possible to either store on site or in a centralized facility, even future technologies like transmutation could be on the table in the future.

In terms of disposal, currently there is only one operational disposal facility for low and intermediate level waste in Różan. Although there is an objective to develop a deep geologic repository in the future which is likely to be preceded by an underground demonstration facility, the timeline is based on having it available by the time the power plants are being decommissioned. As the power plants have not been constructed yet, there is time before action needs to be taken.

3.2. PANEL ON NAVIGATING STAKEHOLDERS ENGAGEMENT: SHARING INSIGHTS AND LESSONS LEARNED IN SPENT FUEL MANAGEMENT STRATEGY IMPLEMENTATION IN MEMBER STATES

Sixty years ago, locating and developing nuclear facilities was undertaken on national interest grounds and the local communities were rarely consulted. The promise of clean, plentiful, and cheap electricity promoted the industry. Over time anti proliferation movements, concerns over nuclear waste and nuclear events have raised the profile and awareness of the public that nuclear activities represented a risk and installed a mentality in some countries of ‘not in my back yard’.

To manage these concerns, it became increasingly important for the industry to engage with the public and to work with local communities to provide information, foster open dialogue and gain in transparency. While there is currently an increasing support and acceptance by the public and pressure groups that nuclear power offers benefits in terms of tackling global warming, this is not necessarily the case when it comes to siting fuel cycle facilities and especially waste disposal facilities. The panel on stakeholder engagement brings together a cross section of people from public representative, university, and waste management organizations to share their experiences, and approaches to stakeholder engagement.

This panel comprised of five presentations, one from Canada, one from Finland, one from France, one from the Netherlands and one from Spain, and it was moderated by Ms Irena Chatzis from the IAEA.

Presenters and titles of the presentations are listed in Table 3. A summary of the main topics of discussion during the panel is included as well as extended abstracts and papers related to the presentations.

TABLE 3. PRESENTATIONS FROM PANEL ON NAVIGATING STAKEHOLDERS ENGAGEMENT: SHARING INSIGHTS AND LESSONS LEARNED IN SPENT FUEL MANAGEMENT STRATEGY IMPLEMENTATION IN MEMBER STATES

Panel moderator: Irena Chatzis (IAEA)		
Country	Presenter	Title
Canada	L. Frizzell	Canada’s Plan for Used Nuclear Fuel
Finland	M. Kojo	Residents' Opinions on the Options for Managing Nuclear Waste from SMRs: The Case of Four Largest Cities in Finland (Paper ID79)
France	R. Zirovnik	Nuclear Fuel Management in France: Balance, Tensions, and Environmental Impacts.
Netherlands	J. Boelen	To Maintain a Meaningful Conversation
Spain	M. Pérez Fernández	Enresa: Creating Community

This is the summary of the discussions during the Panel on Navigating Stakeholders Engagement: Sharing Insights and Lessons Learned in Spent Fuel Management Strategy Implementation in Member States in the format of questions and answers, followed by the corresponding submitted papers and extended abstracts.

Q1: How do you attract and sustain the interest of stakeholders over these very long timeframes, especially after a facility is operational?

L. Frizzell: The first ingredient is listening. NWMO's best experiences have come from following the audience's lead. Doing this results in the right material being prepared at the right level of information using the adequate tools and platforms. Communities' liaison committees have volunteers to facilitate learning induced roles. This provides continuity as it has been sustained even when there have been changes in the communities because of local elections, for example.

J. Boelen: Agreed that listening is the most important factor. When facilities become operational the excitement disappears. Plants look stable but they change and if an event occurs then this will erode trust, therefore it is important to continue engaging but it is difficult to find things that keep the stakeholders interested.

M. Kojo: Surveys of residents in areas such as Helsinki in Finland show that many respondents do not know what Posiva is, as the company focuses its stakeholder engagement in the areas in which Posiva is working. Promises made related to managing only a certain amount of nuclear waste, are hard to change when facilities became operational.

R. Zirovnik: Nuclear industry needs to explain why, where, and how to Local Information Committees (CLIs). It is important to keep the door open and to invite stakeholders to visit the facilities to keep and foster trust. When the public understands the reasons why and have enough knowledge about safety aspects, they have different opinions to normal citizens even if they remain not nuclear supportive.

M. Pérez Fernández: Opening doors is normal practice, coupled with proactive communications and sharing information. As an example, ENRESA organizes, every two years, an international seminar on environmental journalism that includes a visit to facilities. We also organize other open door activities for journalists and the general public.

Q2: How do stakeholder engagement strategies evolve and how do you accommodate changes?

L. Frizzell: Things do change and so does knowledge. You need to be upfront about changes, open and transparent. How you can structure and sustain engagement is down to long term planning, being upfront about the process you are going to use and how it is going to be managed.

M. Pérez Fernández: We need to be able to adapt engagement for the younger generation as they communicate in a different way, both in Spain and abroad.

M. Kojo: Things do change, and an example is reprocessing. A reform of the Nuclear Energy Act is going on in Finland and it is being considered for discussion whether it is plausible or not to import waste. It is necessary to understand how local and international stakeholders think about this topic. There is also the issue of procedural justice that comes with the different changes taking place. What kind of guarantee can be given, for example, for the local community, and what are the decision making tools they have. Because also the legislation changes and then the role or the power of the community might change. We need to be able to think about these different aspects of justice too.

J. Boelen: It helps if organizations incorporate young people as they communicate differently, e.g. using social media. You can implement new forms of communication, but you need to ensure that you are using the right platform, so you need to stay in touch with the community through new ways of communication. Changes in the Netherlands are about new builds which will impact COVRA. We can say what COVRA thinks about the impact will be, but we need to ask the public if they have questions and what their concerns are.

Q3: What are your views on the need for numbers, for example for quantifying the risks, as opposed to say 'good or bad' only? What is your experience working with scientists who are not necessarily good at communicating the message that could be useful for the public?

L. Frizzell: You need to know the audience and where they are coming from. Though it may look like a technical issue, but it could be an emotional issue to the audience. Throwing extensive facts at emotions does not resolve the issue. It is very helpful to engage scientists in communications. NWMO has some wonderful scientists who are also good communicators. As the community learns, the level of questions gets more complicated, but it is not easy as you have to adjust to new people in the audience at the same time.

J. Boelen: The important thing is to get the scientists out of their laboratories. For instance, at COVRA, operators and scientists conduct the tours. This way, people feel they are being taken seriously and the scientists get out and understand that there is a real world beyond the spreadsheets and numbers. It works both ways.

M. Kojo: There are different methods for knowledge coproduction and collaboration, and having scientists on the field can be one way to go forward. The question is who provides the necessary funds to do it. In Sweden the host communities had the opportunity to apply for funding for their communication activities.

Q4: What about engaging with international antinuclear organizations, such as Greenpeace, who can influence the local communities?

R. Zirovnik: The local information committee I am president of, is located near to borders of Luxembourg, Germany and Belgium, and therefore has had cross border involvement for 15 years. There are representatives from both government and NGOs involved and in my CLI, we have a representative from Greenpeace (Luxembourg), who is also a member of the administrative board of ANCCLI. It is good to let antinuclear organizations to express their opinions so we can hear what they have to say. Even if we do not agree we have to be able to talk together in a constructive peaceful way.

L. Frizzell: Anybody with an interest has the opportunity to be involved even if they are opposed to the building of a DGR in Canada. NWMO also reaches out to opposition groups. It is about understanding their concerns and finding common ground. It also helps us to understand the big picture.

M. Pérez Fernández: ENRESA's experience has been frustrating. We have worked with organizations such as the World Wildlife Fund and Greenpeace for a long time and have been open and transparent. But, when we invite them to visit facilities or attend workshops, they refuse to attend and on the other hand claim that we are not being transparent. When we interact privately, the interaction goes smoothly; however, when it is public, they seem to be less friendly towards us.

J. Boelen: Not all NGOs are the same. In COVRA's case, some NGOs we only see in court and others invited me to participate on a panel to explain what we are doing.

Q5: How do you encourage people to be open to new ideas when facts are not always what persuades people?

L. Frizzell: There are no formulae to adopt, it is down to relationships and values. You need to find out what is driving the concerns. First looked at values. Looking at spent fuel management a set of new common values was created, for example to avoid imposing a burden to future generations and others. This helps to find a basis to start the discussion. We had a person totally opposed to the project attending a meeting who was only there to share her opposing views. They were still opposed when they left but they expressed they no longer knew why after having the project team listening to their concerns and a long discussion with them.

J. Boelen: Some of our visitors are nervous when they visit the site for the first time and when they find nothing wrong and find out that this is all there is, then it transforms in a good experience.

L. Frizzell: Telling people is one thing but showing is a 'game changer'. Bringing people to test and real facilities helps them to visualize what is going on, the size of the facility, safety measurements, etc.

Q6: *Trust is important but there are different types of trust, what are the different types of trust you have found and how do you leverage?*

M. Kojo: Finland is seen as a high trust country. A paper published comparing trust in Finland with France showed that the difference in the way society has developed, gives an easier starting point to build trust in Finland than in France. Likewise, the way some societies have developed has led to mistrust.

L. Frizzell: Canadian experience has shown that trust is built through many conversations. People become trusted if they do what they say. Secondly, every interaction is an opportunity to build trust. As relationships are built, trust is propagated which results in referrals that you are trustworthy.

M. Pérez Fernández: In Spain people do not trust by definition. To build trust, you need to adopt a consistent approach, to commit and stay as long as required to discuss. This requires to be done all the time by all.

Q7: *Why was the location of COVRA moved?*

J. Boelen: COVRA is an independent waste management company that is privately owned, and it is not associated with the NPP. If COVRA would have been built next to the NPP then it would have been seen as part of the NPP so the perception would have been different. Being located within an industrial site jointly with other industries avoids this somehow.

Q8: *What role have economic incentives played in attracting communities and has this influenced their involvement?*

L. Frizzell: In Canada no economic incentive was offered upfront to the communities. However, a commitment was made to ensure that they did not have to use their own funds to advance the project. Finance has been provided to make resources available for learning, holding meetings, etc. There was also a commitment to implement the project in a way that advances the wellbeing over the long term of the communities that were involved. As the project has progressed, this has been realized for example by sponsoring local initiatives that are meaningful for the communities, for example in training in transferable skills. We have also recently been negotiating hosting agreements that set out the commitments, the roles, and the expectations we have of each other, including the types of investments that will be made going forward, if the community is successful in the process. Do get push back as investment is seen as buying support, this is viewed as insulting to the communities that have extensively studied the project from every angle. There are other reasons for communities to be engaged as those with mining or transport skills which would benefit the project.

J. Boelen: One of the main concerns around providing economic incentives to communities to accept a facility, when it is perceived as a hazard, is that this approach contradicts the message saying that the facility is safe and there is nothing to worry about, as giving an incentive suggests the opposite. However, most businesses will invest in their local communities, therefore investing as a business is a normal practice for every industry.

M. Pérez Fernández: Money has always been part of the Spanish model. Those that get involved do so because they want more money for the local entities or municipalities. Community projects, however, have to be 50% funded locally and there are caveats in getting the funding such as maintaining the environment, etc.

M. Kojo: In Finland information on local compensations was not available in the late 1990s (at the time of the site selection). It is important that the main actors discuss the process used, who got or will get the benefits, etc.

Moderator's Take Aways (Irena Chatzis, IAEA)

- There were several common themes expressed during the panel discussion.
- These were related to listening to all points of view, being open, transparent, inviting people in and showing them reality or what you planned to do, allowing them to take the lead so responses could be targeted, install learning, and above all keeping communities and public in general informed as the project progresses from the start to the end of operations.
- Learning from one another is paramount and highlights the importance of sharing lessons learned. Not only in stakeholder engagement but for all aspects of the nuclear fuel cycle development and implementation.

CANADA'S PLAN FOR USED NUCLEAR FUEL

L. FRIZZELL

Nuclear Waste Management Organization (NWMO)
Canada

Extended Abstract

The Nuclear Waste Management Organization (NWMO) was set-up in 2002 by the Canadian spent fuel owners in response to the Canadian government's Nuclear Fuel Waste Act on the long term management of spent fuel. The plan being implemented, which relates to the development of a deep geologic disposal facility, emerged through public dialogue and is known as Adaptive Phased Management (APM).

The first step in the plan was to find a suitable site through a site selection process. This process was developed through extensive public input.

Launched in 2010, twenty-two communities expressed an interest in learning about the project and exploring their potential to host it. The process was facilitated using Learn More Agreements, where the communities are provided with the resources, and they need to explore their interest in hosting the repository. Learning more about the programme promoted dialogue, built awareness, and made communities more comfortable considering the idea of hosting the project and whether it would be a fit in their area.

The success of a plan can only happen with the participation and support of Indigenous people. Over the years NWMO has identified ways to foster dialogue, demonstrate transparency, and align with indigenous knowledge alongside western science in our work.

The process to date has resulted in two potential siting areas, both in the province of Ontario.

The NWMO is in the process of finalizing hosting agreements with the siting communities and will select a site later this year. These agreements are one of the last pieces of information the communities need to understand exactly what they are signing up for if they take on this project. After these agreements are finalized, municipal and Indigenous communities in the siting areas will decide if they want to proceed.

Outside of our siting communities, NWMO has built strong relationships with provincial and federal officials to ensure they recognize the need for Canada's plan and understand Canada's stringent regulatory standards. NWMO has also engaged with a wide range of non-governmental interest groups from environmental organizations to labour unions and community associations, all of whom have important voices that will shape the future of this project.

NWMO learned a lot from others around the world undertaking similar projects and understands that we also have a role to play in sharing our experience to help make solutions for the safe, long term management of spent nuclear fuel viable around the world.

As the world moves to meet the growing demand for clean energy, international cooperation has never been more important.

RESIDENTS' OPINIONS ON THE OPTIONS FOR MANAGING NUCLEAR WASTE FROM SMRS: THE CASE OF FOUR LARGEST CITIES IN FINLAND

(PAPER ID79)

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Abstract

In Finland, a number of cities, including notably those in the Helsinki metropolitan area, have proposed small modular nuclear reactors (SMRs) as a means of decarbonizing district heating. The current plans are mainly based on light water reactor technology. Other designs are considered for industrial use. Among the many issues to be addressed before SMRs can become a reality is the management of spent nuclear fuel (SNF). The paper explores the opinions of residents in the Helsinki metropolitan area on selected nuclear waste management options. These include disposal in a centralized national nuclear waste repository, SNF disposal in the municipality hosting an SMR, and exporting the SNF abroad. Finland is a pioneer in the final disposal of SNF. The responsibility for NWM rests upon the waste producer. In 1995, the current nuclear power utilities, Teollisuuden Voima and Fortum Power and Heat, set up a joint company, Posiva Ltd, to prepare for the disposal of SNF. However, the cooperation among companies has not always been frictionless, especially between the incumbents and the prospective newcomers. The ownership arrangements for possible SMRs would therefore be bound to crucially shape NWM in Finland. The views of the local residents play a vital role in determining appropriate and acceptable ownership and waste management arrangements, not least because many municipalities are, through municipal energy companies, also shareholders of TVO and Fortum. Exploring residents' views on various aspects of SMR waste management is important, because for the residents in the Helsinki metropolitan area, nuclear waste is one of the most important issues to consider in a possible SMR project, along with safety and site selection. The research provides information on residents' preferences concerning NWM strategies and explores how socio-demographic background variables and varying levels of acceptance influence their views.

1. INTRODUCTION

In Finland, there is increased interest in small modular reactors (SMRs). Several major cities see them as a possible means of decarbonizing their district heating, but companies, experts, and local authorities are also exploring the possibilities of using SMRs for the production of low-carbon industrial process heat, and for research activities [1, 2, 3]. However, there is currently no clear view on how to deal with the nuclear waste from the potential SMRs.

Finland is a pioneer in the final disposal of SNF, poised to have the world's first deep geological repository for spent nuclear fuel (SNF) in operation by 2025. However, the ONKALO repository, constructed by the nuclear operators' joint nuclear waste management (NWM) company, Posiva, does not have guaranteed final disposal capacity for new operators, as shown by the refusal of Posiva's owners to accept SNF from the planned but later cancelled Fennovoima nuclear power plant (NPP). Even the Ministry of Economic Affairs and the Employment (MEAE) intervened, urging the companies to collaborate [4]. As a result, the companies agreed to cooperate on R&D related to final disposal, but Fennovoima would need to find its solution for the final disposal of SNF [5]. Therefore, national responsibility for the final disposal of SNF in Finland does not automatically mean a joint disposal facility, but newcomers need to be prepared to find an NWM solution of

their own. It can be anticipated that the ownership structure of potential SMR companies will influence whether the possible newcomers can organize NWM in cooperation with Posiva and its owners, Teollisuuden Voima (TVO) and Fortum Power and Heat (FPH). However, as the business models and feasibility studies for the possible SMRs are still under development, there are currently no company-specific plans for NWM from such reactors. The choice of the specific SMR technology, among the many currently under development, will determine the characteristics of the waste and therefore also the options for its handling and disposal [6].

Besides ownership, business models, and reactor designs, one important factor in planning NWM is public acceptance. The topic of social acceptability was already evoked in recent research involving stakeholder interviews in some Finnish municipalities [7, 8]. This research also involved analysis on the regulatory framework, as well as on the implications that the choices between alternative commercial light water SMR designs would have on the final disposal of SNF [7, 8]. However, so far, little attention has been paid to local acceptance and residents' opinions in the debate on alternative NWM principles.

The current Nuclear Energy Act sets national responsibility and the licence holder's obligation as the overarching principles for planning, but given that national responsibility can be implemented in several ways (e.g. a centralized repository or each operator's own repository) and the overall reform of the Nuclear Energy Act is underway [9, 10, 11], it is useful to consider the principles also from the perspective of the residents.

Although public support for nuclear power and possible SMRs is currently record high in Finland [12, 13], opinions vary on nuclear waste and its management. Only 32% of residents of the four largest cities in Finland would accept final disposal of SNF from SMRs in their home municipality [1]. The topic is important, because the residents of the Helsinki metropolitan area consider nuclear waste as one of the most crucial aspects influencing their views on SMR siting. The paper explores the opinions of residents in the Helsinki metropolitan area and in the city of Tampere on the options for the management of SNF from SMRs, the safety of final disposal, transportation risks, and trust in the key actors. Our research questions are: (1) What are residents' opinions on the safety of final disposal of SNF from SMRs? (2) How do safety opinions differ by background variables (gender, age, and political party affiliation)? (3) What are residents' opinions on the options for managing waste from SMRs and how do they differ by gender? (4) How do residents' transportation risk perceptions differ by gender? (5) How does trust in actors differ by gender? Opinions were asked about the following NWM options: a) disposal in a centralized national nuclear waste repository, b) disposal in the municipality hosting an SMR, and c) exporting the SNF abroad.

Section 2 introduces the Finnish nuclear waste management context. Section 3 presents the data and methods. The analysis in section 4 is divided into two sub-sections, the first (4.1) focusing on the respondents' perceptions concerning the safety of the final disposal of SNF, and the second (4.2) on the respondents' opinions on NWM options. Subsection 4.3 presents selected additional findings concerning the opinions on the NWM of SMRs. Section 5 discusses the results, paying particular attention to the alternative societal approaches that should be considered when planning the NWM of SMRs. In Section 6, we conclude that the key actors need to be more outspoken about the options regarding the methodologies and locations envisaged for SMR waste management, given that the citizens' views on NWM principles are diverse, hesitant, and sometimes internally contradictory.

2. SMR NUCLEAR WASTE MANAGEMENT: THE FINNISH CONTEXT AND NATIONAL RESPONSIBILITY

NWM is an integral part of the possible commissioning of SMRs. Compared to other countries producing nuclear energy, the planning and construction of the repository for SNF has proceeded smoothly in Finland. However, the ONKALO repository constructed by Posiva does not automatically provide final disposal capacity for new operators, for example for possible SMR operators.

Since the mid-1990s, the Finnish SNF management policy has adopted permanent disposal in Finland as the preferred option, with waste producers (licence holders) being responsible for the planning, implementation, and costs. In practice, this refers to final geological disposal. Before that, Finland was part of international

efforts at closing the fuel cycle. Between 1981 and 1996, SNF from the Loviisa NPP was returned to the Soviet Union (since 1991, Russian Federation). All SNF produced by TVO's NPPs is in temporary storage at Olkiluoto.

In the 1970s there were plans to establish a state-owned NWM agency [14]. However, the plans did not materialize and the responsibility for NWM was given to the waste producers, i.e. the licence holders. Licensees were also obliged to bear all the costs of NWM. The obligation would also apply to any possible SMR licence holders. The steering of nuclear waste policy remained with the ministry responsible for energy policy, whereas the Radiation and Nuclear Safety Authority (STUK) was given the task of safety assessment and surveillance.

In the late 1970s, TVO began planning for a repository (today known as ONKALO), which is expected to start operation soon. Already in the 1980s, the Olkiluoto site in the municipality of Eurajoki was one of the options. In 1995, the current nuclear power utilities, TVO and IVO (today, Fortum Power and Heat), set up a joint company, Posiva, to prepare for the disposal of SNF from their NPPs. The cooperation started because an amendment to the Nuclear Energy Act banned the export and import of nuclear waste. The exception mentioned in the Nuclear Energy Act was the spent fuel from the FiR1 research reactor, which was returned to the USA in 2021. [15, 1].

An Environmental Impact Assessment procedure of Posiva's final disposal project was conducted in 1997-1999. Posiva and its owners negotiated the Vuojoki contract in 1998-1999 which was vital in enabling Posiva to obtain approval from the municipality in 2000. Soon thereafter, the government issued a Decision-in-Principle (DiP), ratified by Parliament in May 2001. [16, 14.] Since then, the disposal capacity of the plant has been expanded from 4000 tU to 6500 tU. Fennovoima, founded in 2007, sought an agreement with Posiva and its owners on the right to use ONKALO for the disposal of the SNF from its planned NPP unit. No agreement was reached, but instead the Government obliged Fennovoima to start planning and siting its own disposal facility [4, 17]. During the dispute, Fennovoima proposed increasing the capacity of Posiva's disposal facility to at least 18000 tU [4].

Posiva [18] submitted the licence application for the encapsulation and final disposal facility of SNF in December 2021. Recently STUK [19] announced that it needed more time for the safety assessment of Posiva's application. Given that Prime Minister Orpo's [20] government programme is very pro-nuclear, Posiva's licence application is unlikely to face opposition in the government. So far, none of the companies planning SMRs have made any public requests to Posiva and its owners to expand ONKALO's disposal capacity. However, the Ecomodernist Society of Finland has called for a removal of the nuclear waste import and export ban from the Nuclear Energy Act, and proposed NWM services as a major Finnish export product [11]. In a 2016 survey, Finns rejected the idea that nuclear waste imports would be allowed [21]. It is worth noting that the veto right of the municipality of Eurajoki on the possible extension of the disposal facility further constrains the NWM options [17].

3. DATA AND METHODS

A resident survey was conducted to find out respondents' attitudes towards the introduction of small nuclear power plants in Finland and in their own municipality. In addition, the questionnaire covered various topics related to small nuclear power, including those concerning the management of the SNF from possible small reactors. The survey was answered by 2104 Finnish speaking residents aged 18–75 in Helsinki, Espoo, Vantaa, and Tampere. Of the respondents, 46.9% were male and 51.4% female, 1% were of other genders and 1.1% did not wish to indicate their gender. The data was collected as a web based survey for Innolink's consumer panel between November and December 2022, with a margin of error of 2.1%. The gender distribution of respondents corresponded to that of the region in question. The age distribution of the respondents also followed the age distribution of the local population, although respondents aged 60–69 were over-represented and the youngest age groups (under 30) slightly under-represented in the data. The respondents were more likely to be higher educated and in the highest income brackets, while low-income groups (under €20 000 per year) were clearly under-represented [9].

The resident survey was conducted in reaction to the discussions about the possible deployment of SMRs and the ongoing reform of the country’s Nuclear Energy Act, designed to address the specific needs of SMRs. The survey consisted of two screener questions and multiple-choice questions, as well as two open-ended questions. The respondents were asked to answer all screener questions, whereas they could leave some or all of the others questions unanswered.

4. RESULTS

This section presents those results of the survey that concern nuclear waste and spent nuclear fuel management. Section 4.1 reports on the residents’ perception about the safety of disposing of nuclear waste from SMRs in the Finnish bedrock. Section 4.2 presents residents’ opinions regarding the options for managing SMR waste, while section 4.3 summarizes selected supporting findings from the survey analysis.

4.1. Perceptions concerning the safety of the final disposal of SNF

In 2001, the Finnish parliament approved the decision-in-principle to dispose of the spent nuclear fuel from the already existing Finnish NPPs at Olkiluoto, in the municipality of Eurajoki. Posiva’s disposal facility is to start operating in the mid-2020s. However, the residents of large cities do not unreservedly support the disposal of nuclear waste from SMRs [1]. As few as 41% of the respondents agreed while 27% disagreed with the statement “Nuclear waste from small nuclear power plants can be safely disposed of in the Finnish bedrock” [1] (Fig. 1). The rest (32%) did not express their opinion.

In a national survey conducted by the industry association Finnish Energy in autumn 2023, 46% of the respondents agreed and 25 % disagreed with the statement “Nuclear waste can be safely disposed of in the Finnish bedrock” [12], while 29% answered it was difficult to say [12].

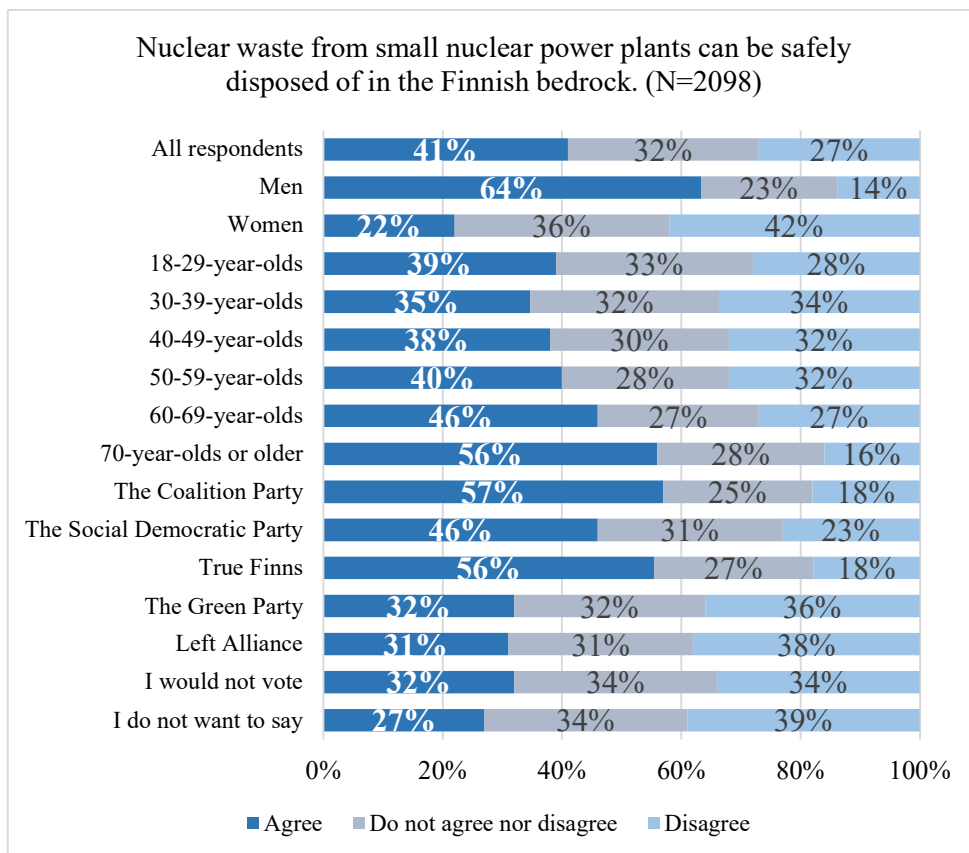


FIG. 1. The opinions of the residents of the Helsinki metropolitan area and Tampere on the statement “Nuclear waste from small nuclear power plants can be safely disposed of in the Finnish bedrock” [1], including examination by gender (male–female), age, and political orientation.

4.2. Residents' opinions on SNF management options

As shown in Fig. 2, the majority of the respondents (58 %) agreed that the waste management of small nuclear power plants should be organized centrally. Only nine percent of the respondents disagreed. The centralization option gets support also from the fact that 38% of the respondents agreed that each host locality or the smallest operators cannot be required to have their own arrangements for nuclear waste management. Although the centralization principle is supported, only 30% of the respondents would support a centralized final disposal of SNF in Olkiluoto. As many as 54% of the respondents were unable or unwilling to express their position on the option of centralized disposal of SNF from SMRs in Olkiluoto. Had the final repository currently under construction in Olkiluoto been explicitly mentioned in the question, the proportion of those who expressed their position could have been higher. Summing up, the centralization principle was supported by the majority in the resident survey, but the siting of such a centralized repository remains an open question [1].

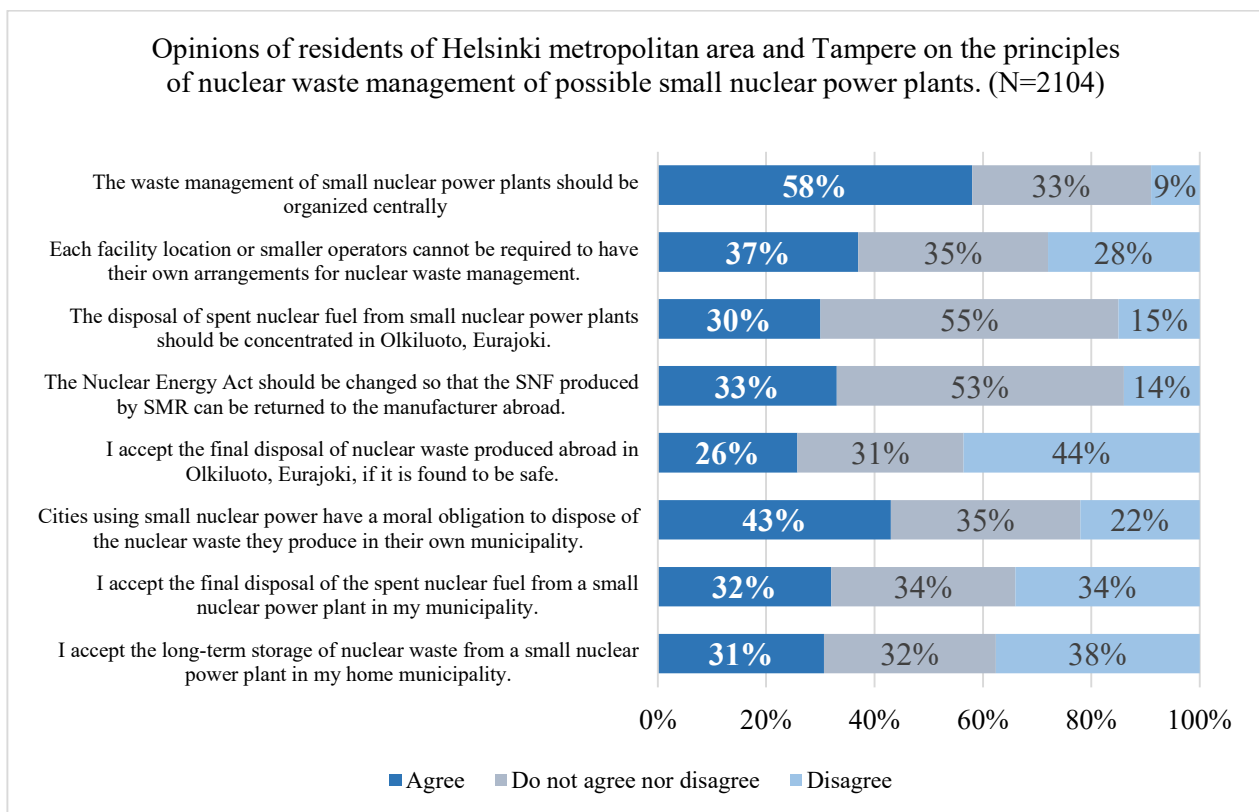


FIG. 2. Opinions of residents of the Helsinki metropolitan area and Tampere on the principles of nuclear waste management of possible small nuclear power plants (N=2104).

The second most popular among the suggested SNF management principles was one according to which the city using a small nuclear power plant also has a moral obligation to dispose of, in their own territory, the nuclear waste they produce. This statement met the agreement of 43% of the respondents, while 35% neither agreed nor disagreed, and 22% disagreed.

Although the statement of the moral responsibility of a city using nuclear power received support, only 32% of the respondents would accept the final disposal of the SNF from a small nuclear power plant in their municipality. However, the majority (55%) of the respondents would accept that a small nuclear power plant be sited in their municipality. It seems that the residents are ready to relax their principled moral argument in favour of 'producer responsibility' if their hometown is suggested as the site for SNF disposal. About a third (34%) of the respondents would not accept final disposal in their home municipality [1].

Interestingly, long term interim storage of nuclear waste in the respondent’s home municipality received slightly less support (31%) and more opposition (38%) than the final disposal of nuclear waste in the respondent’s home municipality (Fig. 2).

The third most preferred principle was to return the waste abroad. About a third (34%) of the respondents agreed with the statement “The Nuclear Energy Act should be changed so that the spent nuclear fuel produced by a small nuclear power plant can be returned to the manufacturer abroad” [1]. However, more than half (52%) of the respondents could not or did not want to express their position, while 14% disagreed. The hesitancy may stem from the fact that the principle of national responsibility for final disposal and the export and import ban are enshrined in the law governing NWM in Finland today. Of the respondents, 27% would approve and 44% disapprove the nuclear waste imported from abroad to be disposed of in Olkiluoto, Eurajoki. Our survey suggests that the residents of large cities are more open to the idea of nuclear waste imports than Finns on average. In a 2016 national survey, only a good 10% of respondents agreed with the statement “I accept the final disposal of nuclear waste produced abroad in Olkiluoto, Eurajoki, if it is found to be safe” [18], whereas almost three out of four respondents disagreed [18].

Attitudes of the respondents towards the NWM principles varied also according to the gender (Fig. 3). Although most women (52%) support centralized nuclear waste management, this option receives even greater support (65%) among men. Women were also more hesitant than men to accept a modification of the Nuclear Energy Act to allow the export of nuclear waste. Among both men and women, most did not express their view on the option of returning nuclear waste abroad to the manufacturer. On the other hand, women (49%) more often than men (36%) agreed that the city using small nuclear power also had the moral obligation to dispose of the waste from these reactors in its territory [1].

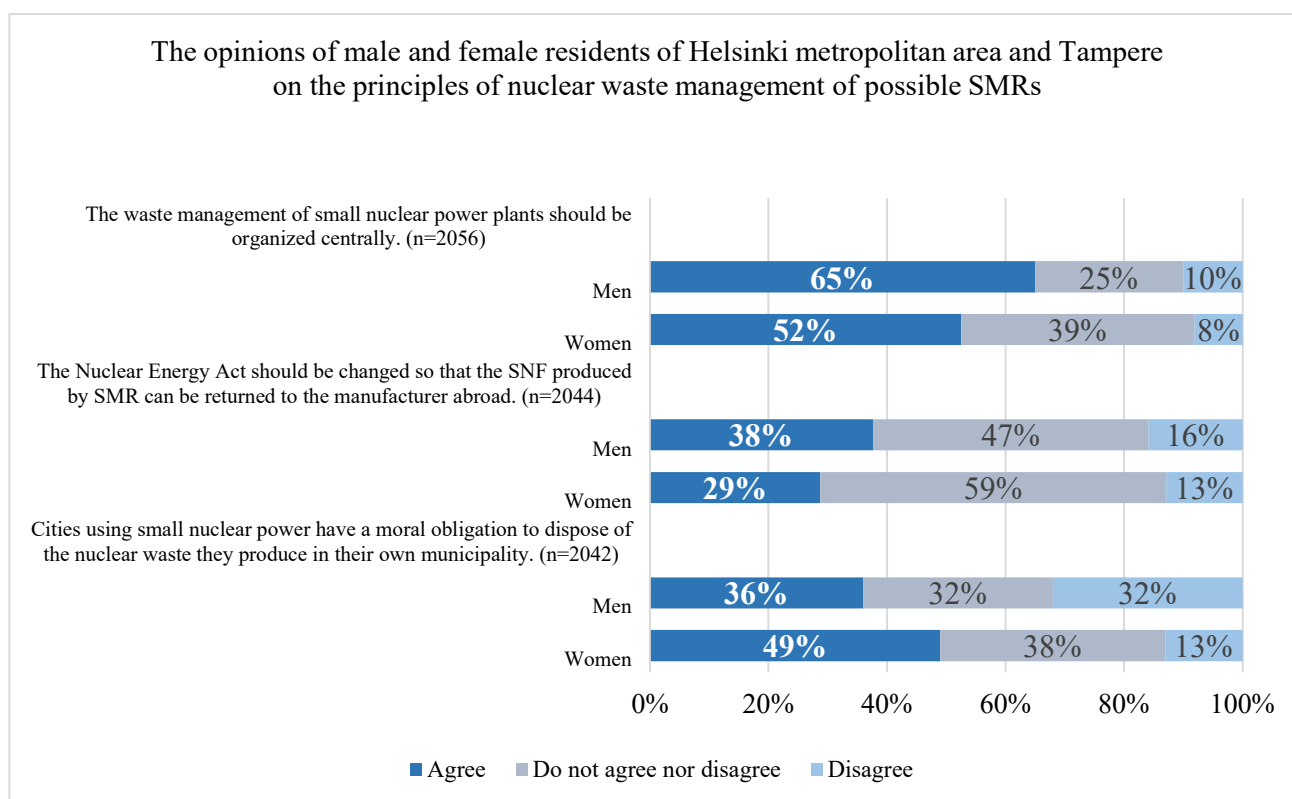


FIG. 3. Opinions of male and female residents of the Helsinki metropolitan area and Tampere on the principles of nuclear waste management of possible small nuclear power plants.

4.3. Additional findings and highlights

Interestingly, 40% of men agreed with the statement “The transportation of nuclear waste produced by small nuclear power plants involves significant risks” [1], while 39% neither agreed nor disagreed with this

statement. Among women, 60% agreed with the statement and 33% neither agreed nor disagreed with it, suggesting that especially women doubt the safety of nuclear waste transports within the country.

The residents were asked about their trust in different actors and institutions involved in the planning of a possible SMR. In response to the question “To what extent do you trust the following actors in the preparation and decision-making regarding small nuclear power plants?” [1], the most highly trusted institution was STUK, with 71% of the respondents expressing high trust (74% of men and 70% of women). By contrast, only 35% of men and 13% of women expressed high trust in the nuclear waste disposal company, Posiva. An explanation might be that the company is little known by the public, as 42% of men and 53% of women responded that they had neither high nor low level of trust in Posiva [22].

5. DISCUSSION

Growing enthusiasm, perhaps hype, around SMRs at the international level [23] has overshadowed the intricate question of what to do with the waste from potential SMRs. The paucity of public debate on this topic, coupled with the absence of earlier research, underlines the need for investigation of public opinions. Despite the planned deployment of SMRs in densely populated regions, there is little information on citizen views on NWM principles and options. This study addressed this lacuna by scrutinizing residents’ perceptions concerning the safety of SMRs’ waste disposal, the available NWM alternatives, transport related risks, and trust in various involved key stakeholders. It is imperative that authorities, financiers, project planners, policymakers and the media have access to reliable information on public opinions. This is particularly crucial now, as the viability of investing in and constructing SMRs is being explored, alongside considerations relating to the social acceptability of the SMRs, and to the legitimacy and credibility of the SMR promise.

Even though most respondents were in favour of centralized NWM, not as many are willing to accept the disposal of SNF from possible SMRs in Olkiluoto. Similarly, 40% of men and 60% of women considered SMR waste transports risky. These findings suggest that if residents’ views are heard, new disposal facilities would be needed. This raises the question about the constraints that social acceptability and geology may pose for the search of a possible new SNF repository site [24]. Moreover, only 41% of the respondents found disposing of nuclear waste in the Finnish bedrock safe. The combination of a centralized NWM solution and SMRs built in various locations across the country would imply more nuclear waste transports and a greater need for research concerning suitable disposal locations.

Recent analysis of the Finnish SMR attitudes [25] have found that although right wing political affiliation and perceived trust in STUK partly explain the differences in public perceptions, the acceptance and perceived safety of SMRs have gender specific variation: women perceive SMRs more often as unsafe, and they are also less supportive of SMRs than men. These findings lend support to earlier research, which has repeatedly shown a significant gap between the perceptions of men and women in their attitudes towards nuclear technologies [25]. Earlier research has suggested numerous and complex theoretical explanations to this gender gap, with those relating to the societal position and vulnerabilities as the dominant ones. As the results of this study show, gender specificities are manifest also in residents’ views on NWM principles and should be considered in policymaking.

Given the growing interest and increasingly concrete plans for the introduction of SMRs in Finland, there is an acute need to consider the principles for the organization of NWM from possible future SMRs. The timing is particularly opportune now, with the overall reform of the Nuclear Energy Act underway. The possible introduction of SMRs at various locations in Finland could result in a situation where decentralized nuclear power production gives rise to decentralized NWM. It is to be expected that companies would seek collaborative centralized waste disposal solutions, for cost reasons in particular, but past experience shows that agreeing on cooperation can be difficult if not impossible, even in the presence of government backing.

6. CONCLUSIONS

The key research question posed in this article was how residents in the largest Finnish cities perceive the NWM options for SMRs. The results of the public opinion survey reveal a mixed picture on the question of NWM principles. On the one hand, most respondents (58%) were in favour of a centralized solution. On the other hand, especially women emphasize the moral obligation of the host municipality of an SMR to dispose of nuclear waste on its own territory (43% of all respondents agree, 49% of women). The debate is further complicated by the fact that only 32% of respondents would agree with SNF disposal in their own municipality and 34% supported the idea of returning nuclear waste to a foreign manufacturer. It is also noteworthy that the proportion of respondents who were unable or unwilling to give their opinion was at least 25% for all statements examined. This suggests that the majority among the general public still has only a vague idea of SMRs and, by implication, of the associated NWM options. Our findings lead us to assert that it is imperative to initiate public discussion on the ethical principles underpinning the NWM of the possible SMRs, notably on aspects related to distributive, procedural, and recognition justice [17]. The key actors (potential licensees, authorities, politicians, and experts) should actively stimulate such debates on the ethical principles, and also be more explicit about the options regarding the methodologies and locations envisaged for NWM.

ACKNOWLEDGEMENTS

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NUCLEAR FUEL MANAGEMENT IN FRANCE: BALANCE, TENSIONS, AND ENVIRONMENTAL IMPACTS

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Extended Abstract

In France, we are extraordinarily lucky that the Environmental Code gives citizens the right to express their views on nuclear issues through the Commissions Locales d'Information (CLIs) and their federation ANCCLI.

CLIs and ANCCLI are neutral structures, made up of representatives of citizens and local players (elected representatives, associations, unions, qualified individuals) living nearby nuclear facilities. The CLIs represent the local voice of civil society, while the ANCCLI acts as a national liaison for the 35 CLIs and maintain the link and coordination between the local and national levels.

The diversity of CLI and ANCCLI members is an asset. The richness of this plurality of expression challenges the players to a common goal:

- Reinforcing safety;
- Transparency;
- Ensuring access to information.

CLIs and ANCCLI are in daily contact with operators, the Autorité de Sûreté Nucléaire (ASN), and the technical supporting organization (Institut de Radioprotection et de Sûreté Nucléaire (IRSN)). They have become players in their own right.

One of the essential missions of the CLIs is to relay information to the general public (the 'Grand Public'), enabling citizens to have their own opinions about the sensitive subject of nuclear energy.

The CLIs question the operators (Électricité de France (EDF), Orano, Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA), Agence nationale pour la gestion des déchets radioactifs (ANDRA)), ASN and IRSN, organize debates, carry out counter analyses, monitor the environment, undertake expert appraisals, and take part in inspections.

The work of the CLIs is widely disseminated to the general public and institutional partners via newsletters, public meetings, press articles and their website.

The latest ANCCLI White Paper: NUCLEAR FUEL MANAGEMENT IN FRANCE: BALANCE, TENSIONS, and ENVIRONMENTAL IMPACTS

As part of its mission, ANCCLI exchanges and works with CLIs' members on any subject related to the operation of a nuclear facility. These subjects may concern governance, safety, the environment, radiation protection, waste management, decommissioning, transparency, or access to information.

In some cases, this work has led ANCCLI to draft White Papers. A White Paper is both a work of general information, providing factual and precise information on a given subject. On the other hand, a white paper enables CLIs to convey to operators and institutions the point of view of civil society, the questions it raises and the recommendations it puts forward.

In its latest White Paper, the tenth since the ANCCLI was founded in 2000, the ANCCLI deals with fuel management in France on 3 main points:

- Balance of fuel management in the context of mono recycling of fuel in the form of MOX;
- Tensions on flows and facilities;
- Environmental impacts;

This white paper has 4 objectives:

- Provide an initial overview of the fuel cycle;
- Raise awareness and educate CLIs on the various issues raised by this subject; publicize the diversity of viewpoints expressed by CLIs;
- Make proposals to institutions and operators;
- Finally, the White Paper details the reasons why ANCCLI intends to contribute to transparency and information on nuclear fuel management, in line with its missions.

For ANCCLI, the current fuel management policy appears fragile for several reasons:

- The risk of storage pools becoming saturated (a risk that seems to be receding in view of the change in France's energy policy);
- Difficulty of manufacturing MOX fuel, with a dedicated plant undergoing restructuring and process changes;
- The aging of processing and recycling facilities.

Beyond short term responses to these disruptions, the CLIs and ANCCLI are also keen to ensure that clear longer-term perspectives are mapped out, and that the consequences of the various possible scenarios are transparently assessed within the framework of clearly established governance, taking into account the evolution of energy choices.

As part of its mission to provide information and contribute to the transparency of nuclear activities, ANCCLI is particularly attentive to ensuring that these issues are clear and well understood for citizens, especially those living close to the various nuclear facilities involved.

ANCCLI is also keen to ensure that taken decisions are in compliance with the Aarhus Convention.

For instance, the centralized spent fuel storage pool topic is very messy and uneasy to understand for citizens and it can lead to a lack of confidence.

- For some years now, French nuclear operators have been facing a major problem: the saturation of spent fuel storage pools, both at EDF and Orano;
- This forecast led the French government, in its national plan for the management of radioactive materials and waste, to ask operators to provide a solution to this saturation;
- The centralized storage pool was due to be built before 2030, but the project put forward by the operator gives a deadline of 2034, and the latest news is that the pool will not be needed immediately (not before 2040), particularly in view of the change in energy policy, which provides for continued operation of 900 MW(e) and 1300 MW(e) reactors;
- CLI and ANCCLI have been involved and kept regularly informed about this issue since 2018;
- This famous pool was supposed to be built on the territory of Belleville-sur-Loire, in the middle of France. As local stakeholders and the population were opposed, plans were changed;
- In the end, the pool project ended up in La Hague area, which is already heavily nuclearized and this, without finally answering the main question: Where do exactly will stand the pool?;
- The public debate on this new chosen territory was very hard, with a lot of protest. Still today, we are told that saturation is not for 2029 and even not before 2040!

In its White Paper, ANCCLI alerts us to decisions taken regarding the recovery of radioactive substances or their management as waste, and their consequences, which may be economic or environmental in nature, or concern nuclear safety and the radiation protection of workers and the population.

ANCCLI therefore considers it particularly important to contribute to the transparency and understanding of decisions concerning nuclear fuel management. It contributed to the drafting of the latest national plan for the management of radioactive materials and waste. It participates in various national working groups with operators and institutions to ensure that the plan is properly applied and that it is consistent with energy policy decisions.

The large number of operators involved (Orano, Framatome, EDF, CEA, ANDRA, etc.) and the fluctuating nature of public decisions in the nuclear field mean that special efforts are required to make nuclear fuel management understandable to the general public, and thus to ensure the transparency that contributes to good anticipation of decisions taken in this area.

The technical nature of the issues at stake in fuel management policy makes it difficult to grasp in a cross-disciplinary and comprehensive way.

The organization of CLIs and ANCCLI at both territorial and national levels is therefore a valuable resource for dealing effectively with the issues involved.

TO MAINTAIN A MEANINGFUL CONVERSATION

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Extended Abstract

To maintain a meaningful conversation involves hard work, long term commitment, to be open and to tell stories based on facts. So, the story of COVRA in the Netherlands.

COVRA is the only company in the Netherlands tasked with the integrated waste management for all Dutch radioactive waste. The company is today just 40 years young considering the long time frames it is concerned with. Current forecasts run up to 2200. This long term view is the starting point in considerations on the development of its infrastructure, maintenance, waste packages, site, organization etc. For instance, being located in an industrial site alongside chemical and production industries means that there will always be trained engineers that can be recruited. We are part of an industrial ecosystem that cannot be created by the company on its own.

We are now a valued member of the community. Back in 1990 at the start, there was a different perspective. We were not so welcome in the area as the original plan was to locate the facilities in between the existing NPP and the nearest local village. By listening and taking the concerns seriously and moving the facilities into the adjacent industrial park itself, the issue was resolved. However, the experience showed us that we needed a communications strategy if we were here to stay.

COVRA's strategy is based on three elements: Open up, Invite in, Show what is happening and comeback please. This approach is not common in the industry, and nuclear waste is not an easy story to tell. People have difficulty grasping for instance the very long time frames associated with decay for certain types of waste.

To tell our story we decided to do this through art. Art has the ability to connect people at an emotional level, not by fact and figures. We engaged Willian Verstraeten (artist) a well known regional artist. His idea was to show the public what is happening inside the bunkers of concrete and steel. By looking at the outside the public are given a sense of what is happening on the inside, this is imagined through repainting the building over time reflecting material decay (starting with flaming orange (danger!) and gradually changing the shade over a hundred year period until it ends up white (safe)). The dedicated depleted uranium storage building is shaped as Europe's largest sundial which is slowly ticking the time away.

We like people to visit; so we create opportunities for people to meet and organize regular art exhibitions. The opening of the HLW store was held inside the storage facility itself and opened by the then Queen. Building on this, last year we had a music festival over five days adjacent to the HLW store, within the nuclear site, with over a hundred people attending each night. The way to store waste for the long term is similar to preserving a museum collection. Together with the main regional museums we have created a real art museum inside the storage building for low and intermediate level radioactive waste. Visiting the museum is therefore a means to engage people and a demonstrating of safety.

We are still young organization set on maintaining a meaningful conversation with our community. This requires a mindset of transparency, long term commitment, effort and to tell a story not just facts.

ENRESA: CREATING COMMUNITY

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Extended Abstract

Identification of Enresa's stakeholder groups

Enresa is the public company responsible for managing radioactive waste in Spain, and it also handles the dismantling of nuclear facilities. Enresa has identified the following stakeholder groups:

- (1) Twelve external and national groups, grouped into 4 categories: decision makers (including institutional control bodies to which Enresa has to report to, other public administrations that can influence its activities, and shareholders), opinion leaders, the nuclear sector, and populations in areas of influence;
- (2) One external international group consisting of international organizations with which there is a relationship of collaboration and exchange of information and knowledge;
- (3) One internal group, the employees of Enresa, with no hierarchical or organizational unit distinction.

Enresa is in constant communication with each of these groups, utilizing various established communication channels.

Current relationship with stakeholders

Due to its public nature and the essential service, it provides for the country, Enresa maintains an open, constant, and transparent relationship with its various stakeholder groups. Enresa's transparency and social responsibility policy is outlined in the 7th General Plan for Radioactive Waste, the document that sets the company's activity line.

Currently, the relationship with stakeholders is based on the following premises:

- (1) Clear and transparent information: The company strives to provide rigorous information tailored to the final recipient to ensure an understanding of our activities;
- (2) Agile regulatory compliance: Enresa, in addition to providing technical solutions, is responsible for paying municipalities that meet the requirements the allocations set by ministerial order and co-financing local development projects as stipulated by law. Enresa has recent cases of working to adapt laws to the company's new realities;
- (3) Smooth and friendly relations with municipalities: Beyond a more traditional institutional relationship, Enresa maintains a close relationship with them, face-to-face with the municipalities in the areas where we operate, being the first to know their demands and concerns;
- (4) Quick informational response and open-door policy: The media are another crucial stakeholder for publicizing Enresa's activities. Enresa maintains a proactive attitude in informing about its projects, as well as a rigorous and quick response to any information request. We carry out an open-door policy at our facilities allowing them to get to know us, interview our spokespersons, and form their own opinions has proven to be one of the most effective ways for good dissemination of our activities.

Within the current relationship with stakeholders, the employee collective stands out, for whom Enresa is currently developing an important Internal Communication Plan with multiple tools such as newsletters, intranet, screens, emails, events, etc.

Lessons learned

Enresa is a public company supervised by the ministry responsible for energy or the environment. Over its nearly 40-year history, Enresa has undertaken various projects with different communication and social strategies, yielding different results, not always attributable to the company itself.

Centralized temporary storage: from state project to political project

The 6th General Plan for Radioactive Waste, approved in 2006, established a single Centralized Temporary Storage (CTS) as the management strategy for spent fuel and high level waste, in line with the 9th Resolution unanimously approved by the Industry Committee of the Spanish Congress in December 2004. For years, the CTS was a strategic project for the company, which tried to launch it under the slogan ‘a State Project’ to avoid ideological associations with any political party.

With a location already assigned, initially, the central government, the autonomous community, and the municipality were all under the same political party, and the project was closely linked to the leaders of that time. Spain is divided into 17 autonomous communities, which are territorial entities with autonomy, institutions, and representatives, and certain legislative, executive, and administrative competencies, making them similar to federated entities in many respects. Therefore, it is not only necessary to consider the central executive but also the community executive. A few years later, the opposing political party came to power in the autonomous community and immediately warned that it did not want the project in its territory. The project, instead of being seen as a State Project, was perceived as a Political Project, significantly affecting its development.

In the strategic environmental study of the 7th General Plan for Radioactive Waste, which gave a voice to all the autonomous communities, none wanted to host this storage facility in their territory. Consequently, the new plan, approved in December 2023, changed the strategy to on-site temporary storage at the nuclear power plants as a preliminary step to a deep geological repository.

Dismantling and decommissioning project of Garoña NPP: building trust from the start

In contrast to the CTS project, the dismantling and decommissioning of the Santa María de Garoña nuclear power plant, which Enresa took over in July 2023, is proceeding differently.

Before starting the dismantling and decommissioning project, Enresa prepared a comprehensive communication strategy to introduce itself in this new environment. Key elements of this strategy included thorough close, and complete information across multiple formats; a deployment plan involving all stakeholders; and an open-door policy from the first day of the project. The goal was to build a trust-based relationship with the new environment.

And so, it was. In the first months, Enresa welcomed various audiences to the facility, showing them everything that would be done, when it would be done, and who would do it. Additionally, active listening allowed the visits to be tailored to the expectations of each visitor. This has helped Enresa become the main source of information about the project and establish the close relationship it sought.

Current relationship tools with stakeholders and effectiveness level

Enresa’s Communication Plan includes multiple tools for engaging with the media and other stakeholders. These tools include face-to-face interactions, press releases, statements, or magazines both digital and print.

We have a Virtual Classroom, after detecting the lack of educational and academic information about our activities; we have developed social media profiles (Facebook, Instagram, X, YouTube, Flickr, and LinkedIn), and our follower communities are steadily growing.

However, we want to highlight that generating quality content is fundamental for all these tools, so Enresa devotes significant effort to generating interest. For example, organizing its own events like the International Journalism and Environment Seminar; educational talks from El Cabril ‘Charlas Chec’; specialized courses at universities; among others.

Conflict resolution

Fortunately, Enresa experiences little internal conflict. Sometimes conflicts arise externally, so Enresa has a well defined technical profile and never engages in matters outside its activity or evaluates decisions from other bodies. This is achieved with a team of spokespersons trained and advised by communication experts who deliver the appropriate message at each moment.

Moreover, Enresa maintains a neutral stance on Nuclear Energy, a contentious debate in Spain, neither defending nor criticizing it as it is not within its remit. Enresa only executes what is stipulated in the General Plan for Radioactive Waste.

Evaluation and control

Materiality Analysis: As part of its sustainability strategy, Enresa conducted a study in 2022 to identify the most relevant issues in its performance concerning economic, governance, social, and environmental dimensions. This work, known as a materiality analysis, allowed the company to analyse the expectations of its stakeholders from the perspective of social responsibility and sustainability, defining the most important aspects for both internal and external stakeholders of the company.

Surveys: Enresa periodically conducts various surveys to analyse the evolution of its image, the satisfaction of some of its stakeholder groups, and the public's knowledge of its activities. The results of these surveys are used to implement new actions or discard less effective ones.

Reports: Enresa regularly produces reports to track the evolution of its communication efforts: press releases, that quantifies media appearances, and the tone used, and the social media report, which captures the growth of followers on different social media platforms and highlights the most impacting contents.

3.3. PANEL ON INNOVATION AND INTEGRATION: APPROACHES FOR MANAGING SPENT FUEL FROM ADVANCED REACTORS

Ever since the discovery of nuclear fission in 1938, nuclear and innovation have been inextricably linked. But not since the original push for power in the mid-twentieth century current levels of excitement and anticipation relating to new nuclear have been seen, not just within the industry, but outside of it too.

With climate change being an important issue with global implications, nuclear has been identified as a large scale low carbon energy source that can be part of the solution. Rising to that challenge, there are many new reactor technologies under development, some quite different from the commercial scale plants in operation today and providing not just power but meeting other needs of heavy industry and society at large.

To complement this innovation in the front end, we also need to innovate in the back end. This could be done through utilizing waste from the current reactors to fuel the next generation or designing fuel cycles that can maximize the fuels' potential to its fullest.

This panel comprised of six presentations, one from the World Nuclear Association (WNA), one from the Joint Research Centre – European Commission (JRC-EC), one from France, one from the United States of America, one from the United Kingdom and one from Canada, and it was moderated by Ms Laura McManniman (EPRI, United States of America).

Presenters and titles of the presentations are listed in Table 4. A summary of the main topics of discussion during Panel 4 is included as well as extended abstracts and papers related to the presentations.

TABLE 4. PRESENTATIONS FROM PANEL ON INNOVATION AND INTEGRATION: APPROACHES FOR MANAGING SPENT FUEL FROM ADVANCED REACTORS

Panel moderator: Laura McManniman (EPRI, United States of America)		
Country	Presenter	Title
WNA	C. Evans	Advanced Recycling Options: Tangible Paths to Unlock the Full Potential of Nuclear Energy (Paper ID53)
JRC-EC	L. Iglesias Pérez	JRC-Euratom Foresight: Anticipating the Future Challenges of Spent Nuclear Fuel Management
France	P. Gauthé	Upcycling Nuclear for Climate
United States of America	E. Petit de Mange	Deployment of a Modern Fuel Recycling Facility: The Favourable Economics for Recycling American Used Nuclear Fuel (Paper ID91)
United Kingdom	B. Merk	IMAGINE – A Breakthrough Nuclear Technology Operating on Spent Fuel Without Prior Reprocessing (Paper ID103)
Canada	A. Situm	The Development of Small Modular Reactor Spent Fuel and Radioactive Waste Strategies for Saskatchewan

This is the summary of the discussions during the Panel on Innovation and Integration: Approaches for Managing Spent Fuel from Advanced Reactors in the format of questions and answers, followed by the corresponding submitted papers and extended abstracts.

Q1: *How important do you think fuel cycle back end innovation is to the success of new reactor technologies?*

B. Merk: Turning the question around, can new technologies help us reduce the size of disposal? We need to move away from the reactor and then face the problem of what do we do with the wastes it produces. Collaboration between the front and back end is key to obtaining an optimized solution.

C. Evans: The industry view is to “meet the moment” rather than wait for the paradise of a perfect solution. There are new users, industry players (not owners of the technology), newer technologies, and deployment in different countries (either close to populations or remote). Technologies will help us address the technology hurdles. Need to master the commercial side and discuss new business practices. There is a change of players proposing different solutions including fuel takeback, fuel leasing, etc. Communications and regulatory framework need to be addressed.

P. Gauthé: It is a matter of credibility and public acceptance because the nuclear sector works with both the reactor and the fuel. New reactors need to tackle new problems, and the back end could be the hardest part. The front end which is addressing global warming is seen as the ‘good guy’ while new wastes are seen the ‘bad guy’. To be credible, you need to provide solutions with less waste and more sustainable energy.

Q2: *In which areas do you think that international collaborations could be enhanced in promoting and delivering innovations for spent fuel management?*

L. Iglesias Pérez: The possibilities of creating a shared solution, shared deep geological repositories is one example where there would be significant benefits. All the improvements could lead to shared solutions.

C. Evans: We are looking at sharing infrastructure and investments but not limited to disposal. Because of the disperse location of spent fuel, we will have to integrate, and we could think about sharing infrastructure, before disposal. Like we have done in the past, with the reprocessing in the UK and France, for instance. So, I think we need to foster that on top of fostering collaboration on the R&D part.

A. Situm: Molten salt reactor waste will need a lot of research and development to be disposed of. This is an important and not solved yet area that is ideal for and would benefit from international collaboration.

B. Merk: It is key how collaboration is structured. Firstly, it needs someone to lead to get it going on and secondly it needs to be focused to provide specific solutions.

Q3: *A lot of the fuel types that are being considered for advanced reactors have been used in some capacity during earlier research. How are you utilizing previous experience and learning?*

P. Gauthé: HEXANA wants to work on the reactor and energy system part and is not interested in making fuel or operating fuel facility. The key for us is the public-private partnerships as well as small -large company partnership. HEXANA is a new company so it cannot do everything but can benefit of performing work with experts in the field.

E. Petit de Mange: Most experience so far is in oxide fuels but there is also experience in metal fuels in several countries and we are leveraging a lot of that operational data in our safety bases, models and in the licensing process. Have to rely on the collected knowledge from operations, etc. as there is no operational fast reactor in the USA, at the moment. The US DOE has on going work programmes to capture as much of that information as possible for posterity so that is very useful from the fuel qualification standpoint.

B. Merk: Small companies have to rely upon technology that is out there or on national programmes. The development and manufacturing of new fuels is a long and expensive process that small companies cannot afford alone.

Q4: *HEXANA and OKLO look to take what is considered today either as a low value resource or a waste and to revitalize it to fuel advanced reactors. From a technology development perspective, what do you think will be the biggest challenge to overcome?*

P. Gauthé: The challenge is to find a market. If a lot of industries are interested in building reactors then this will trigger the investment in the fuel facilities. Alternatively, there has to be a governmental decision to invest in the fuel cycle. The biggest challenge for HEXANA will be to convince the government to invest in a new MOX fuel fabrication plant with a 5—10 tHM/year capacity, a decision which is needed now.

E. Petit de Mange: In the USA, we have a solid customer demand, and the technology is there and has been proven. The real risk is the potential for political friction in terms of safeguarding the facility. At the same time, this could be seen as an opportunity for leading the world, as this could lead to having a facility that sets the standard, in terms of safeguards, for the rest to follow.

Q5: *JRC, in your introduction you outlined the advantages that a foresight approach could bring to managing spent fuel. How has the JRC found such an approach useful in this field?*

L. Iglesias Pérez: The sector is always evolving, and when a new technology comes to the market, this could be developed to make improvements and to help other industries. It is important for the JRC to help in different fields, identifying areas where we can collaborate. For example, artificial intelligence is one area that is being explored by looking into how to incorporate it the regulatory systems.

Q6: *Follow up question, do you have any experience on how the European Commission brought forecast results into something new within European research projects?*

L. Iglesias Pérez: We are looking at the potential recovery of different elements or parts of spent fuel which would be of value.

Q7: *Is the heat storage system technology being used in the HEXANA fast reactor system a new system? And for how long are you planning to store the heat before you use it for industrial applications?*

P. Gauthé: The molten salt heat storage system is not new and currently finds application in the Middle East and other countries. The heat exchanger system which couples the fast reactor to the heat storage system, however, is new. The plan is to locate the heat storage system outside the nuclear site, but still have to demonstrate that in doing that, safety is not affected.

Q8: *Follow up question, by using the heat exchanger, you eliminate the sodium- water interaction. However, in case of leakage there is high risk for corrosion, therefore, are you just trading one problem for another?*

P. Gauthé: Did not say that heat exchanger failure is not a risk. Changing to molten salt removes a pressure risk which is large in the case of sodium water reaction. In the case of molten salt there is no pressure and interaction between mediums is slow and can be detected. The risk is reduced but there is still a reaction possible and therefore the risk of failure has to be managed. The plan is to have modular heat exchanger systems 50 MW, 100 MW, etc. – so if one is lost there is a replacement.

Q9: *In the past there were demonstration plants to debug new technology, what has changed?*

E. Petit de Mange: OKLO's approach involves leveraging the data from previous demonstration plants such as EBR-II and mitigating technological risks not introducing new alloys which have the potential to create

new challenges. Therefore, we are in the position to build a first of a kind recycling plant which will become the first commercial system of its type in the USA.

A. Situm: In the case of molten salt technology, we cannot just jump. In the USA there is Hermes, a TRistructural-ISOtropic (TRISO) fuelled molten salt cooled 35 MW(th) test reactor being evaluated before moving to pilot plants.

B. Merk: If there is sufficient experience, then we can go forward without a demonstration plant. If new, then we need to go through the classical approach to collect data for safety cases and getting the buy-in of key stakeholders such as regulators. It is not just about developing the technology; it is also about growing a team with the knowledge and the ability to operate.

Q10: *Given the uncertainties around whether the current DGR projects will accept SMR fuel, could we end up with a country having more than one DGR?*

A. Situm: New non-nuclear waste and ILW, could be accommodated in a country repository, and might involve the same volunteering community or be sitting in the territory of a different one. However, when it comes to SMR waste, it would likely require approaching the host community once again, which can be an intensive process. It may be easier to talk about LWR fuel, for example, but if you start introducing different spent fuels like TRISO, or molten salt, then it is going to require a new conversation.

B. Merk: The job of the scientist is to identify whether it is possible or not. The role of the politician is to make the decision whether to do it or not to do it. The hard part is to convince people to start this kind of programme, and somebody has to take responsibility and that is the difficulty.

E. Petit de Mange: In the USA, we do not have a repository, but maybe we could look at it as a blessing in disguise. If we had proceeded with the original repository concept, and given the potential growth of the nuclear power in the USA, and advances in the fuel cycle, then potentially in hindsight we may have pursued a repository approach that we came to regret in the future.

Q11: *How do you keep momentum going and turning ideas into reality?*

P. Gauthé: There is a government funded project in France for undertaking feasibility studies into new nuclear startups. Do not need a large amount of funding at the feasibility stage. Moving to the next stages, demonstration, etc. will need to attract interest. A combination of public funding, grants and private sector funding would be required for this. It is unlikely that the more than 80 design concepts for SMRs will all go to completion and there will need to be a selection process.

B. Merk: Communicate at different levels, writing papers, take to the right people in the government, if not receptive then need to look internationally to see if there is interest. Someone has to do the first stage and then others will join.

C. Evans: Currently we see a lot of public funding for reactor design or development. But again, do not forget the fuel cycle. Because if you build the reactor without the fuel cycle, it is not going to work. So, we need to look at the system to be able to deliver both the reactor and the associated fuel cycle.

Q12: *Question to the WNA, the WNA already provides predictions on nuclear energy what is different about the WNA working group on unlocking potential nuclear energy?*

C. Evans: The WNA scenarios look at what is going on in the market up to 2040. The working group looked at longer time frame using the 2040 predictions as the basis for the study.

Key Take Away Messages from Each Panellist

- **A. Situm (Canada):** In terms of DGR, if molten salt reactors are an option going forward and the salt fuel is to be disposed of in a DGR then considerable work will be needed to support this.
- **B. Merk (United Kingdom):** For breakthrough technologies the front and back ends of the fuel cycle need to work together to optimize the problem.
- **E. Petit de Mange (United States of America):** We need to get on with deploying advanced reactors through focusing on what to do to succeed now whilst anticipating the needs for enabling safe and effective management of the back end of the fuel cycle.
- **P. Gauthé (France):** Regarding public acceptance, we have to be unafraid to talk about nuclear waste. The public wants to learn and to be reassured, so it will not be afraid.
- **L. Iglesias Pérez (JRC-EC):** The nuclear waste management sector has a great future. Pulling together people with different backgrounds and knowledge brings new ideas and will lead to improvements in how nuclear waste is managed.
- **C. Evans (WNA):** The back end of the fuel cycle is not an obstacle, but there are some challenges in parts. It can also be an opportunity to deliver nuclear and meet the moment.

Moderator's Take Aways (Laura McManniman, EPRI, United States of America)

- The panellists have discussed many aspects of innovation, which are not only technical and include engagement with stakeholders, international collaboration, sharing infrastructures, etc.
- We need to think about how to innovate collaboratively, how to do it commercially and how to share infrastructure, all the way through the whole fuel cycle not just only thinking about waste disposal.

ADVANCED RECYCLING OPTIONS: TANGIBLE PATHS TO UNLOCK THE FULL POTENTIAL OF NUCLEAR ENERGY

(PAPER ID53)

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Abstract

Any nuclear energy system, i.e. composed of nuclear power plants (NPP) and their associated fuel cycle and waste management, have two fundamental objectives. The safe, secure, economical and/or affordable and sociopolitical acceptable use of nuclear energy which applies both to the NPPs as all undertakings in the nuclear fuel cycle and waste management activities, including the safeguarding of the whole nuclear system; The guarantee of the safe disposal of all radioactive waste generated during the use of nuclear energy not presenting any unacceptable impact on human and environment while not unduly limiting the options that future generations may opt for. The nuclear fuel cycle has been developed from the early days of nuclear energy's use and operated safely, securely, and responsibly since then including the safe transport of all nuclear materials throughout the nuclear fuel cycle. Regarding the ultimate waste management, final disposal options are operational for low level and intermediate level waste categories in most countries where the geological disposal of high level and long lived radioactive waste is advancing well towards operational facilities before mid-century in Finland, Sweden, and France. Other countries presenting progress from R&D until site selection investigations though operational geological disposals scheduled (well) beyond mid-century. Not only such irradiated fuel originated waste are well managed, all other waste from fuel cycle and NPP operations are as well. The paper will essentially focus on used fuel management and related high level waste aspects as being closely related to the strategic reflections regarding tomorrow's even more sustainable nuclear energy systems.

1. INTRODUCTION

Since the early days of nuclear energy use, a growing amount of used nuclear fuel (UNF) has been accumulating in most countries with this UNF essentially interim stored in wet and lately dry storage facilities. While such interim storage of UNF is a necessary operational activity whatever the chosen nuclear fuel cycle option, it cannot be considered as the final responsible destiny for the UNF compliant with the ‘Stage 2’ (see Fig. 1) of the fundamental objectives for nuclear energy [1, 2].

Some countries consider this UNF as being waste and thus a final disposal solution, mostly geological disposal, needs to be developed and operationalized in due time. Other countries regard this UNF as still holding valuable nuclear materials and go for reprocessing of this UNF and recycling of essentially the reprocessed uranium (RepU) and plutonium (Pu) (Option A in Fig. 1) where the fission products and minor actinides end into vitrified high level waste (HLW) for future emplacement in a geological disposal. Here again, such a final disposal as part of Stage 2 remains a necessity.

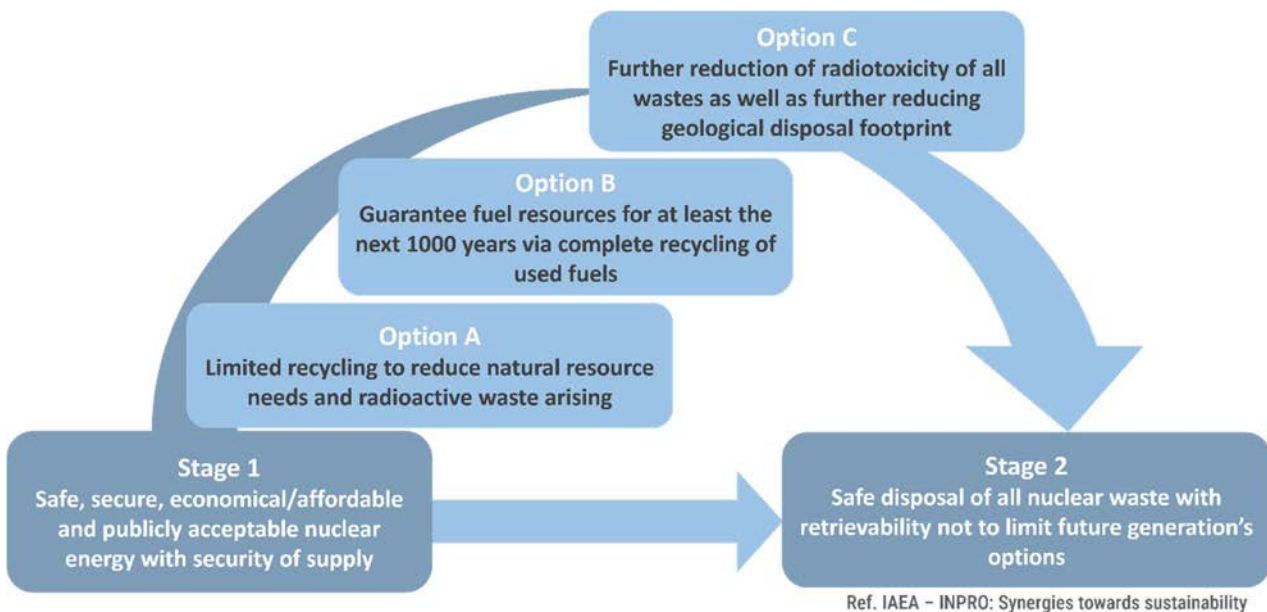


FIG. 1. Fundamental objectives for nuclear energy [1, 2].

The slowdown in deployment of nuclear energy worldwide, since the 1990s, due to a variety of socioeconomic reasons happened parallel to an increased focus on the public acceptable management of long lived radioactive waste which, in most cases, essentially associated to UNF. A sociopolitical perception grew regarding the ‘radioactive waste problem’ combining ‘waste’ and ‘problem’ in one connotation without truly dissecting the specifics of such ‘waste’ and surely not if it is truly a ‘problem’. Particularly the long term radioactive longevity and (reversibility and safeguards indicted) stewardship were increasingly seen as not belonging to good practice and even not considerable for sustainability criteria. The latter having been amplified by the EC’s Sustainable Green Taxonomy considerations where nuclear energy was disregarded due to such deemed ‘unsustainable’ radioactive waste management.

A growing set of (international) programmes were initiated since these early 1990s to investigate more advanced nuclear fuel cycles to essentially:

- Reprocess the UNF and to further the separation of the different nuclides from such UNF, being it RepU, Pu but also the minor actinides (Neptunium (Np), Americium (Am), Curium (Cm)) and even considering the separation of fission products (FPs);
- To further develop more specific waste matrices for these separated materials further improving their conditioning and ultimate disposal, i.e. separation and conditioning strategies;

- And to consider the recycling of these separated nuclear materials beyond the already industrialized RepU and Pu recycling in and ERU (enriched reprocessed uranium) and MOX fuels including the multirecycling in light water reactors (LWRs) (and even CANDU reactors), high temperature reactors (HTR) and towards an introduction of fast reactors (FRs), Molten Salt Reactors (MSRs) or even Accelerator-Driven Systems (ADS). Especially the FR and MSR options currently high on the agenda of the (startup driven) innovations under Advanced Modular Reactors (AMRs).

2. ADVANCED NUCLEAR FUEL CYCLES UNTIL NOW

The anticipated large deployment prospects for nuclear energy considered since the 1970s, driven by the then energy crisis, also projected the possible shortage in a timely availability of natural uranium. This added arguments to develop fast spectrum reactors (FRs) that can better use the natural uranium via an ‘infinite’ recycling of the Pu and breeding of such Pu by irradiation of the depleted uranium (DU) stemming from the front end of the fuel cycle. Such FRs with multirecycling fuel cycle would extend the energy generated from a gram of mined natural uranium a hundredfold and thus provide ample energy for us all (Option B in Fig. 1). This being surely a prime example of what circular economy should be as being increasingly part of the societal objectives since that last 10 - –20 years.

Since the 1990s lead to the ‘Clean Waste – Dirty Fuel’ investigations driven by the sociopolitical concerns regarding the management of the UNF and ultimate radioactive waste impacting the acceptability of nuclear, next to also the quest to further optimize the geological disposal requirements (particularly for those countries lacking such disposal options). These investigations were seeking to reprocess, recycle, and transmute all annoying nuclides in UNF and to drastically reduce the amount as well as drastically reduce the duration of stewardship of the ultimate waste from millions of years to some hundred years. This Partitioning and Transmutation (P&T) advanced fuel cycles (Option C in Fig. 1) were increasingly investigated since these early 1990s, initially in Japan and, later on, even more in EU (France, Belgium, ...) with programmes funded by the EC, as well as, albeit during a shorter period, in the USA (ATW, AAA, AFCI programmes) [3].

Figure 2 shows the evolution of the radiotoxicity for a typical LWR UNF assembly clearly indicating that:

- The prime radiotoxicity is defined by the Pu in the UNF;
- FPs are the second largest contributor to radiotoxicity though largely shorter lived and thus decaying rapidly with only some fission products and activation products, i.e. ^{129}I , ^{36}Cl , ^{79}Se , playing some role in the longer term;
- Of all minor actinides, the prime nuclide to consider is Am;
- In the very long term, the radiotoxicity is again governed by the uranium as it is in natural uranium.

The ‘Clean Waste – Dirty Fuel’ (and thus P&T) considerations largely focused on this radiotoxicity as prime objective for such reduction and shortening of stewardship of disposed waste. Though, well engineered geological disposal facilities do contain such radiotoxicity very well with the radiological risk from such disposed radiotoxicity not presenting particular concerns (see Fig. 3). Only a few long lived and more mobile fission and activation products might be released, albeit well below any regulatory threshold, in the very long term in evolution scenarios even considering degradation of the disposed waste. Only in the, overall very, hypothetical scenario that future generations would seek to mine the disposed radioactive waste would the radiological risk become equal to the then still present radiotoxicity and present a true risk to humans and environment.

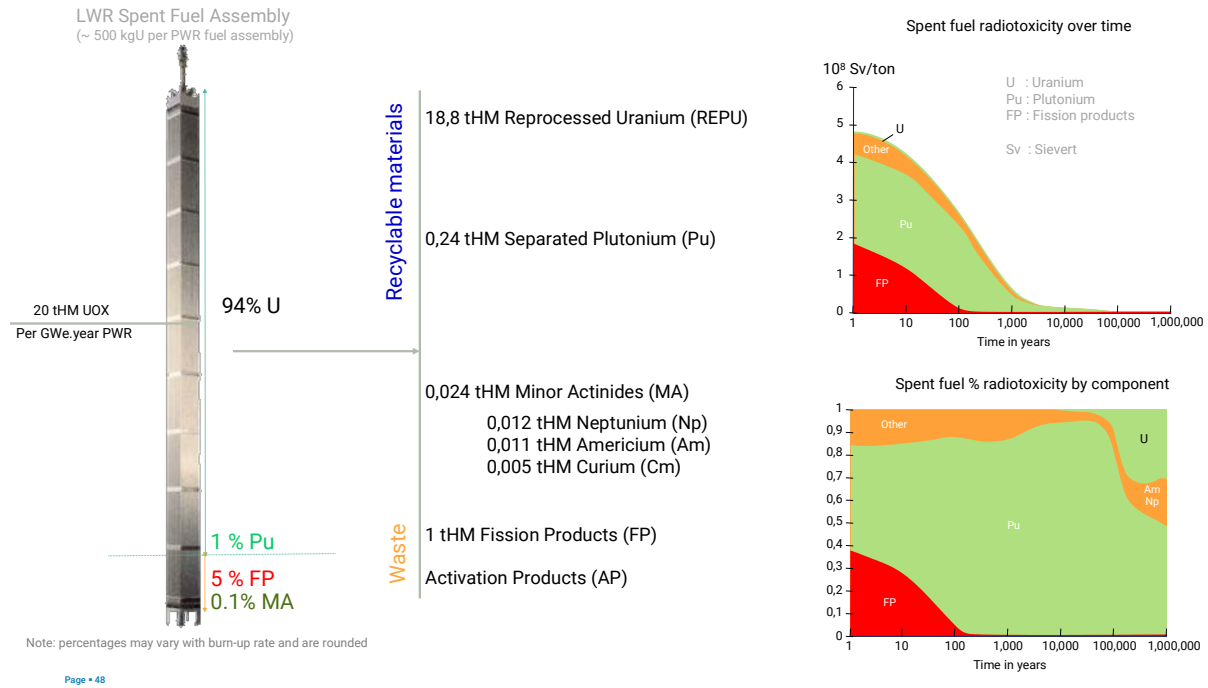


FIG. 2. UNF's composition and evolution of radiotoxicity over time.

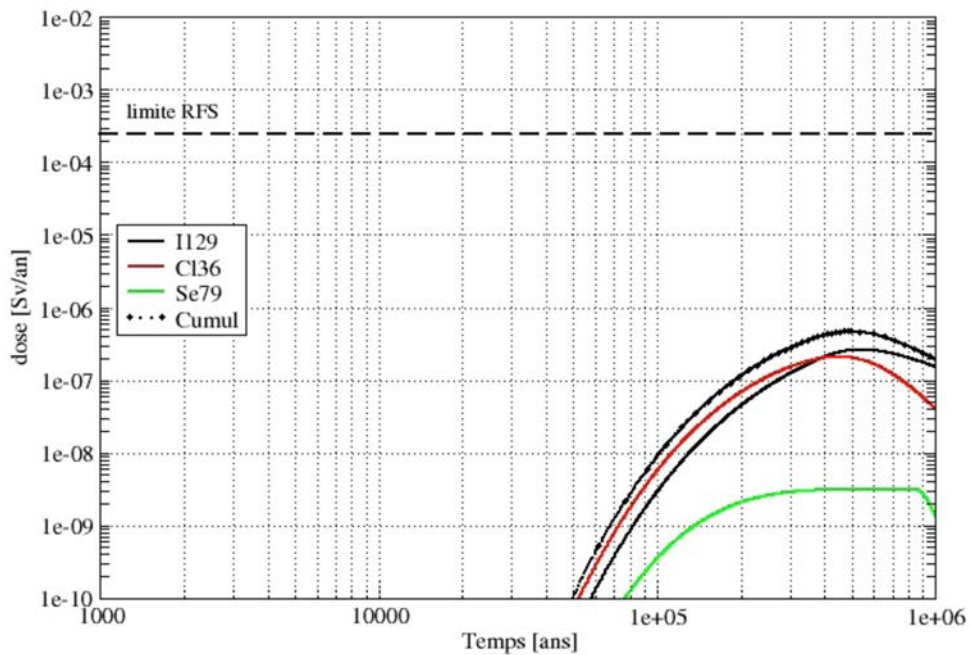


FIG. 3. Radiological risk in typical (clay) geological disposal conditions [4].

While the reduction and shortening of the radiotoxicity is not a real driver from an ultimate waste management perspective, some of the actinides present in UNF do present also a long term residual decay heat which defines the footprint required for the geological disposal facility.

Here, some of the Pu isotopes (²³⁸Pu) and especially ²⁴¹Am do present a long term decay heat impact where the reduction of their amount in to be disposed waste would be beneficial to the geological disposal footprint. Multirecycling of Pu in FRs already reduces the footprint by a factor 7 compared to once-through fuel cycle with the separation and transmutation of ²⁴¹Am allowing an additional reduction by up to about a factor 2 (assuming 120 years of cooling of HLW before disposal) or up to a factor 5 when separating and transmuted

all minor actinides. Remark that such scenario does consider the continued use of nuclear energy during significant time, i.e. centuries, to achieve these objectives at full.

A variety of studies [2, 4, 5] addressing virtually all imaginable advanced fuel cycle options but also the vast industrial practice has concluded quite comparatively as schematized in Fig. 4, i.e.:

- U and Pu management are mature industrialized options in LWRs with an industrial capacity since the 1980s allowing to reduce by some 20% the natural uranium needs per TWh(e) and reducing the amount and longevity of the ultimate waste. In addition, the absence of Pu in such ultimate waste alleviates significantly the safeguarding challenge for disposed UNF;
- Vitrified HLW management also being an industrialized solution awaiting the final disposal on geological disposal facilities;
- Further optimization of the fuel cycle from a waste management perspective being possible, i.e.:
 - From a radiological risk perspective, hardly any benefit comes from the active management of minor actinides via such advanced fuel cycle options. An important element also to be considered being the impact on nuclear fuel cycle operations and associated safety and radiological risks from a more active MA-management in such facilities;
 - Considering only radiotoxicity, i.e. abstraction being made of the isolation function of geological disposal facilities, only Am presents a radiotoxicity risk in the long term;
 - The geological disposal footprint being impacted by the presence of ^{241}Am and thus benefiting of reducing the ^{241}Am content in to-be-disposed waste;
 - From an industrial feasibility perspective, Np is not presenting specific challenges where Am does though, with proper design and subject to technological progress and innovation, might become doable in due time if the benefits of an active management outweigh the technological challenges. Cm being the true bottleneck and largely to be avoided from an active management in industrial fuel cycle facilities.

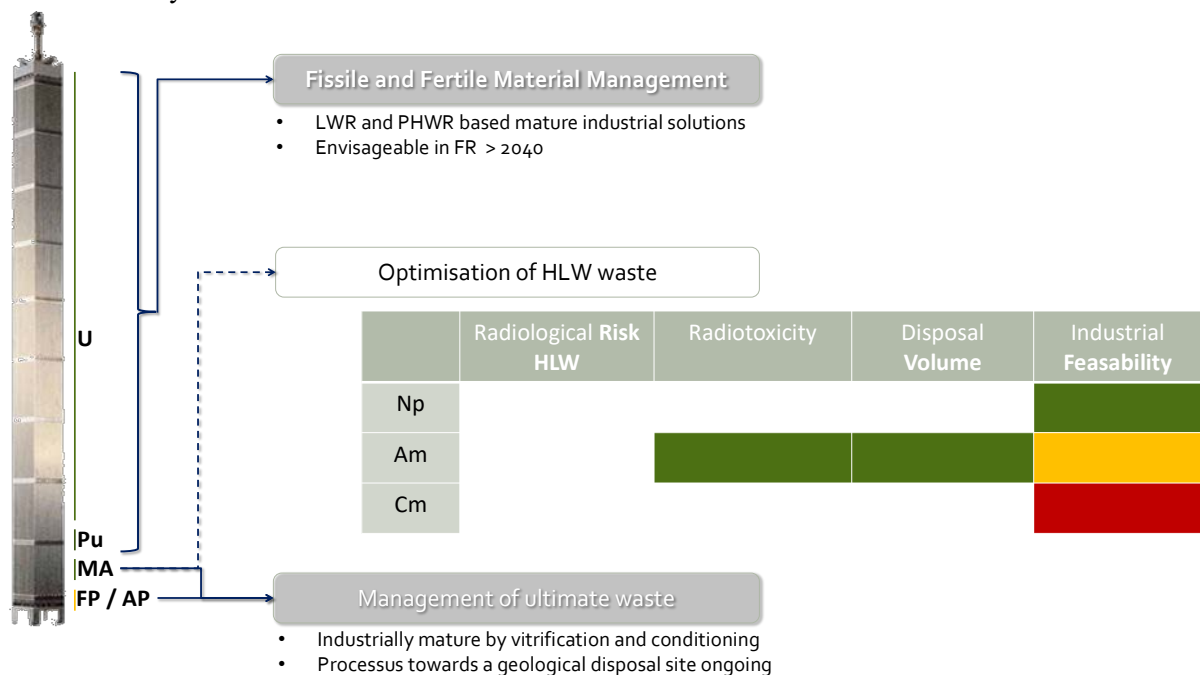


FIG. 4. Summary of studies on advanced fuel cycles.

3. PROSPECTS IN THE NUCLEAR FUEL CYCLE IN THE SHORT TO MEDIUM TERM

The recent WNA report The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2021 - 2040 [6] provides interesting insights in today's and tomorrow's fuel cycle situation and prospects. To be remarked that these prospects are essentially reflecting 'business as usual' scenarios regarding the fuel cycle

operations as most, if not all, of the advanced nuclear energy systems under consideration and development today will only have a significant impact post 2040. The main lessons learned from this Nuclear Fuel Report summarize as follows:

- There is no immediate shortage for natural uranium, in principle, but the estimated primary and secondary sources show an undersupply of the uranium market. The supply gap being unclear today given commercial sensitivity, political or strategic uncertainties next to market volatilities and other factors. The main trigger to fill this gap are more sound prospects for nuclear energy deployment signalling the market to launch more exploration leading to the development of new mining projects;
- The conversion market remains a concentrated market with a small number of companies producing the UO_2 or UF_6 . The last eight years were experiencing an oversupply capacity due to reduced requirements and accumulated UF_6 stockpiles leading towards a reduction, suspension or even closure of conversion production assets. The near term future should lead to resuming some of the idle capacity today, but capacity expansion or new capacity is anyhow required;
- Enrichment faces a rebalancing of the market as underfeeding/tails re-enrichment allowed in Western markets the postponement of new capacity investment while the rapidly growing Chinese market being supplied by anticipated domestic Chinese enrichment capacity expansion. The Ukrainian war leading to a shift away from the Russian enrichment capacity for most Western requirements and hereby also leading to a re-balance accelerating the need for capacity expansion before 2040 in OECD countries;
- The fuel fabrication market, more specific than the previous front end activities, is largely in balance with the requirements though imbalances may occur particularly given new or modified fuel assembly designs becoming demanded for, e.g. LWR technology based Small Modular Reactors (SMRs) from the 2030s on. Overall, fabrication capacity follows neatly the requirements defined by the operational NPP requirements and firm prospects for planned newbuild NPPs;
- In the back end of the nuclear fuel cycle, no significant changes are expected before 2040:
 - Interim storage of used nuclear fuel will continue in reactor pools, centralized pools or mostly in dry storage cask conditions with also a more centralized storage capacity developing as actively promoted within the USA;
 - Reprocessing capacity remains operational in France, the Russian Federation, and, at a smaller capacity, in China and India. The commissioning of the Japanese capacities is scheduled in the 2020's. The renewal of the La Hague reprocessing assets, following a long term continuity plan, are foreseen in the 2040's;
 - Comparable situation applies to the recycling fabrication capacity as the MELOX plant presenting a comparable timeline towards renewal.
- Geological disposal capacity is developing in Finland, Sweden, and France with operational phase starting before or around 2040. Other countries anticipating such repository deployment well beyond mid-century or most of the time even later.

While such conditions provide stability for the coming decade until mid-2030s, the uprise in nuclear energy deployment prospects worldwide will present a challenge during the 2020s:

- These prospects, as promising they may be, they remain still uncertain as:
 - Large LWRs are still being constructed and planned in many countries and these will remain the backbones for nuclear during the decades to come;
 - Though, the small modular reactors (SMRs) are projected being highly in demand, but tangible projects remain to be confirmed enabling technological qualification and demonstration;
 - More advanced nuclear reactors, if small or modular also called 'Advanced Modular Reactors' (AMRs), are projected for post-2035 at the earliest and even longer term well beyond 2040. However, these AMRs will depend heavily on fuel cycle functions as reprocessing and recycling as many present "dirty fuel, clean waste" concepts. As a fall-back position, as many SMRs, they do consider the use of HALEU fuel in the early phases which demands for such HALEU fuel

supply chain capacity as critically defining their prospects. Within the USA, such HALEU fuel supply chain capacity is therefore strongly stimulated.

- An additional uncertainty comes from an overlap with the replacement/renewal timeline for many of the fuel cycle facilities, not at least, those in the back end of the fuel cycle. As mentioned before, the reprocessing and recycling platforms in Europe, i.e. France, are due for renewal around the 2040s while other capacities will need to be considered and/or expanded around the same time-period;
- The longer term future for nuclear energy systems, despite a tremendous wealth in options, does demand some strategic convergence as not all of these options can be industrially developed at the risk of being sub-optimal and not allowing for sufficient economies and/or efficient supply chain deployment. Some structuring questions impacting these futures being:
 - Will ‘radiotoxicity’ for to-be-disposed radioactive waste remain a paramount decisional criterion and being valued even more important than the decarbonization capacity of nuclear energy as such. Authoritative studies worldwide conclude that radiological risk is the real criterion and imminent operational geological repository sites in Finland and Sweden (and later-on France) may well demonstrate to the public at large that such long lived radioactive waste is not really a problem. From a radiological risk perspective, minor actinides are not of significant concern and only the minimization of ²⁴¹Am be a strategic and economic objective through the reduction of the long term decay heat and thus reducing the required footprint of a geological repository or, better, maximizing the capacity of such scarce repositories;
 - This will define the value to be allocated to ‘beyond Pu/U’ recycling schemes aimed at reducing the ‘radiotoxicity’ or, more important, the footprint per TWh(e). The reduction of particularly ²⁴¹Am may well become an important future objective as it would allow to maximize the TWh(e) equivalent capacity for then existing repositories;
- It may also facilitate the prospects for regional repository use as not only the improved capacity use but also the longevity reduction may be valued highly.
- The buy-in from energy-intensive industries to adopt nuclear energy for particularly heat use will be co-defining the type of nuclear power plants, especially SMR/AMRs, making the market. While electricity markets may well be served for long by LWRs, including small LWR type SMRs, higher temperature heat requirements in cogeneration will demand for additional reactor technology deployment. In the medium term, this may be HTR technology based with, later on, liquid metal cooled and molten salt-based systems.

4. THE NEW NUCLEAR – INCREASINGLY CONSIDERING ADVANCED FUEL CYCLES?

In this new context for nuclear, three main developments will define the definition of and the prospects for advanced nuclear fuel cycles, i.e.:

- (1) The growing deployment of large LWR NPPs, still largely the backbone for nuclear energy during this century, will re-stretch the questions posed before, i.e. how to manage the UNF responsibly while seeking to address the socio-political concerns of not executing such UNF management, i.e.:
 - (a) If UNF is considered waste, let’s truly make geological disposal options operational and just do it;
 - (b) If UNF is considered as holding valuable materials, let’s continue and strengthen the capacity for reprocessing and recycling and seek to further such recycling by multirecycling options in LWRs (e.g. MOX2; REMIX) awaiting the introduction of FRs and/or MSR;
 - (c) We do have all studies and largely all preparatory R&D available to execute these options well before the 2050s and already bring an answer to the UNF and ultimate waste management;
- (2) The expected introduction of SMRs will bring new challenges in the nuclear fuel cycle being it the security and safeguarding of more decentralized SMRs and their UNF but also the fuel being used by such SMRs. Some using HALEU UOX fuels which, not only from the front end fuel cycle ask for new investments in particularly enrichment capacity, but also in the back end as the HALEU UNF does present higher Pu-content which may make this UNF more amenable or attractive for reprocessing and recycling of the Pu and RepU;

- (3) The future introduction of AMRs, using more explicitly Pu/TRU content fuels, bring again a new spectrum of fuel cycle options where synergies between LWR/SMRs and such AMRs, next to FR/MSRs, bring additional options to, overall, achieve the Stage 2 via the options A, B or C sketched in Fig. 1.

As such, the connotation ‘advanced’ may bring a new meaning in such new nuclear growth prospects.

Where ‘advanced’ essentially related to the use of technological innovation in the past and largely addressing LWR and LWR+FR nuclear energy systems, tomorrow’s ‘advanced’ may be more diverse composed of:

- *Advanced technological options* as new reprocessing and recycling options next to new fuels (e.g. ATF/eATF), and developments in interim storage, conditioning and disposal solutions (e.g. potential deep borehole);
- *Advanced synergies* between different reactor technologies, e.g. LWR + SMR or later-on LWR + SMR + AMR + FR/MSR, entailing multiple options as:
 - Intra-country synergies within a nuclear fleet, e.g. France, China, India, Russian Federation, where a large-enough and diversified NPP-fleet also allows to further optimize the fuel cycle;
 - Inter-country synergies where UNF/nuclear materials (NM) transfers happen between countries with mutually complementary NPP-fleets and fuel cycle options, e.g. LWR-PHWR for RepU-management, pre-cycling options, fuel takeback;
 - All largely exploiting inter-technology options by, in due time, combining fuel cycles relating to LWRs, SMRs, AMRs, FR/MSRs.
- The associated business models may also bring ‘advanced’ approaches to the nuclear fuel cycle where some fuel cycle companies may present advanced fuel cycle options seeking only the return of FR-holding waste to the country of origin where the TRUs are multiple recycled within these countries operating the fuel cycle facilities and expected to be combined with FR/MSR-capacity.

A variety of scenarios for nuclear energy can be considered with an illustrative set of fuel cycle families sketched in Fig. 5.

The Fig. 5 sketched futures for nuclear energy systems are characterized by two main dimensions defining those, i.e. (vertically) the level of and pace towards decarbonization with (horizontally) the level of systems thinking in designing the overall sustainable energy system and the use if intranuclear synergies.

The four quadrants then lead to different futures from a continuation of today’s (large) LWRs with an open or monorecycling fuel cycle (Nuc BAU) to the extension of the nuclear power park worldwide including SMRs and some advanced nuclear reactors though, as both with limited system synergies, mostly using ‘evolutionary’ process and not making best use of the unique features of nuclear energy. On the right side, using these unique features, one does match the different energy market requirements with the different nuclear power solutions while also exploiting a more integrated nuclear materials management throughout the while nuclear system. This would lead to a high degree of circular economy essentially based on a responsible use of reprocessing and recycling and deploying the international governance for doing so.

The projected NNP parks for the various scenarios are shown in Fig. 6, from current large LWR technologies, encompassing SMR-LWRs, HTGRs, AMRs and FRs.

The Fig. 7 shows the resulting natural uranium requirements and Fig. 8 the UNF arisings for such scenarios, up to even tripling the nuclear power use worldwide, showing that the future (yellow) natural uranium demand may well be important (and even increasing when HALEU fuelled SMRS are used more extensively) though can be circumvented via such synergistically deployed nuclear energy systems.

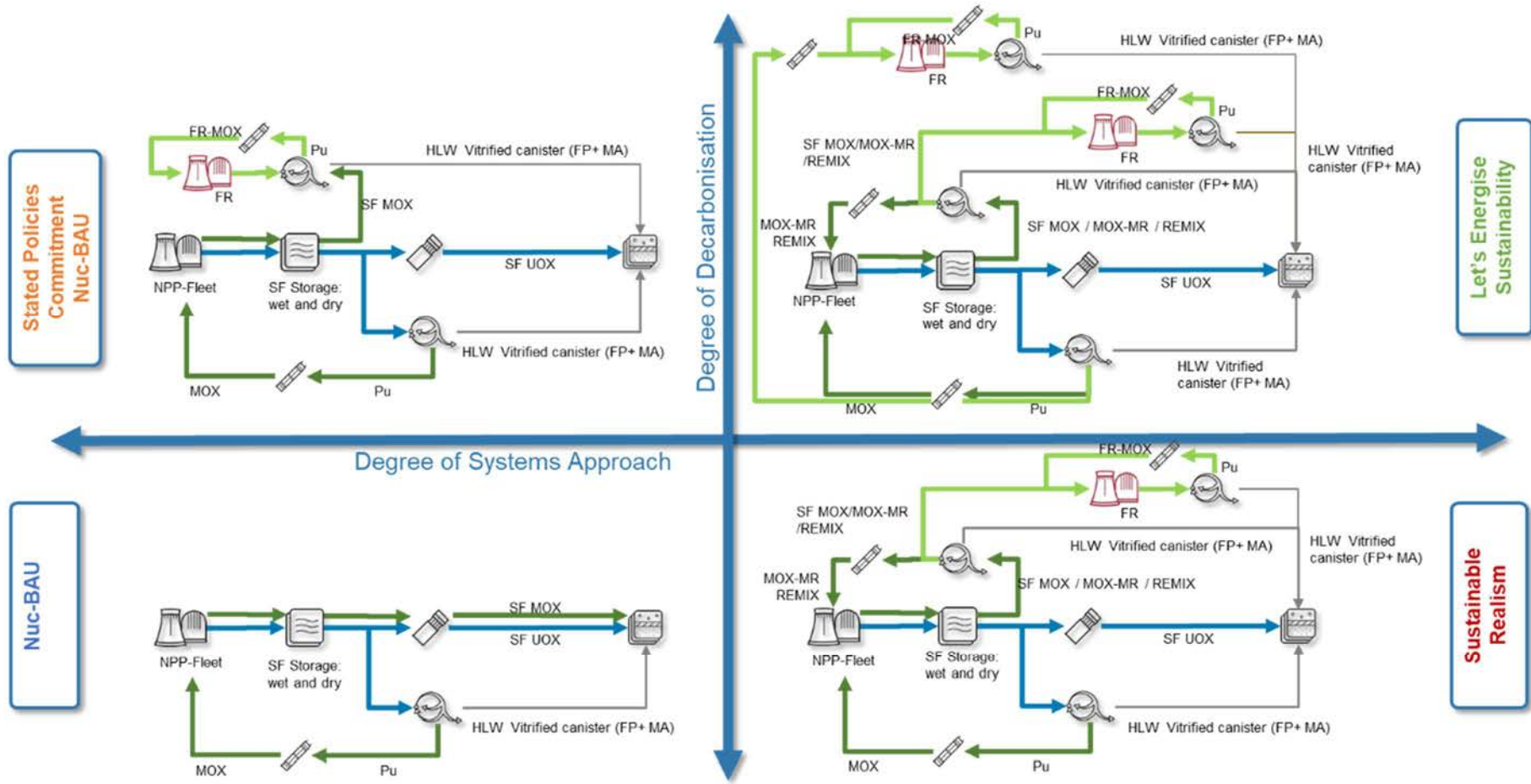


FIG. 5. Nuclear energy systems illustrative for nuclear energy's future families [7].

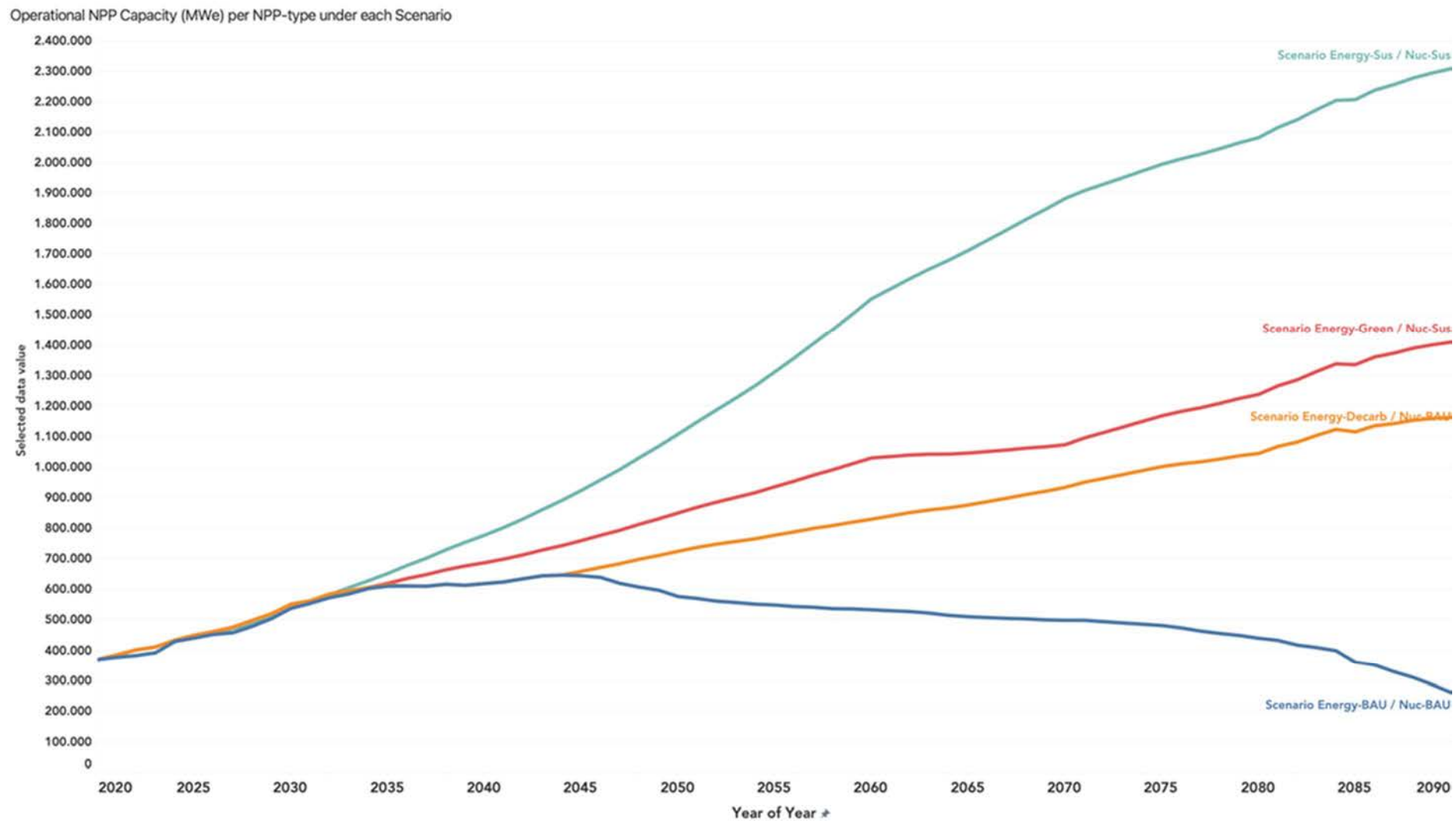


FIG. 6. Projected nuclear capacities for 4 illustrative scenarios.

Unat Requirements (tHM/yr) per NPP-type under each Scenario

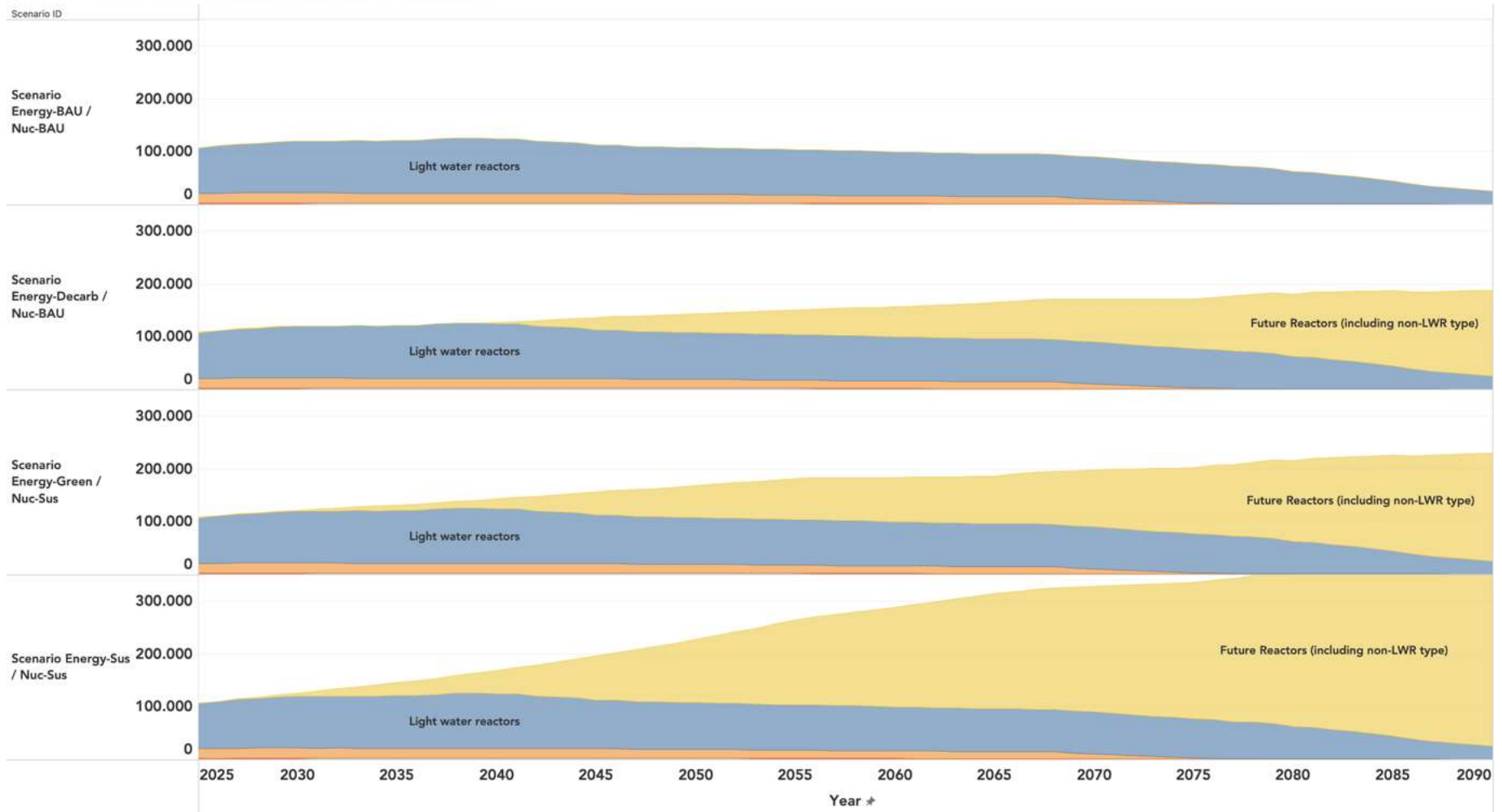


FIG. 7. The amount of Unat required for such scenario.

UNF production (tHM/yr) per NPP-type under each Scenario

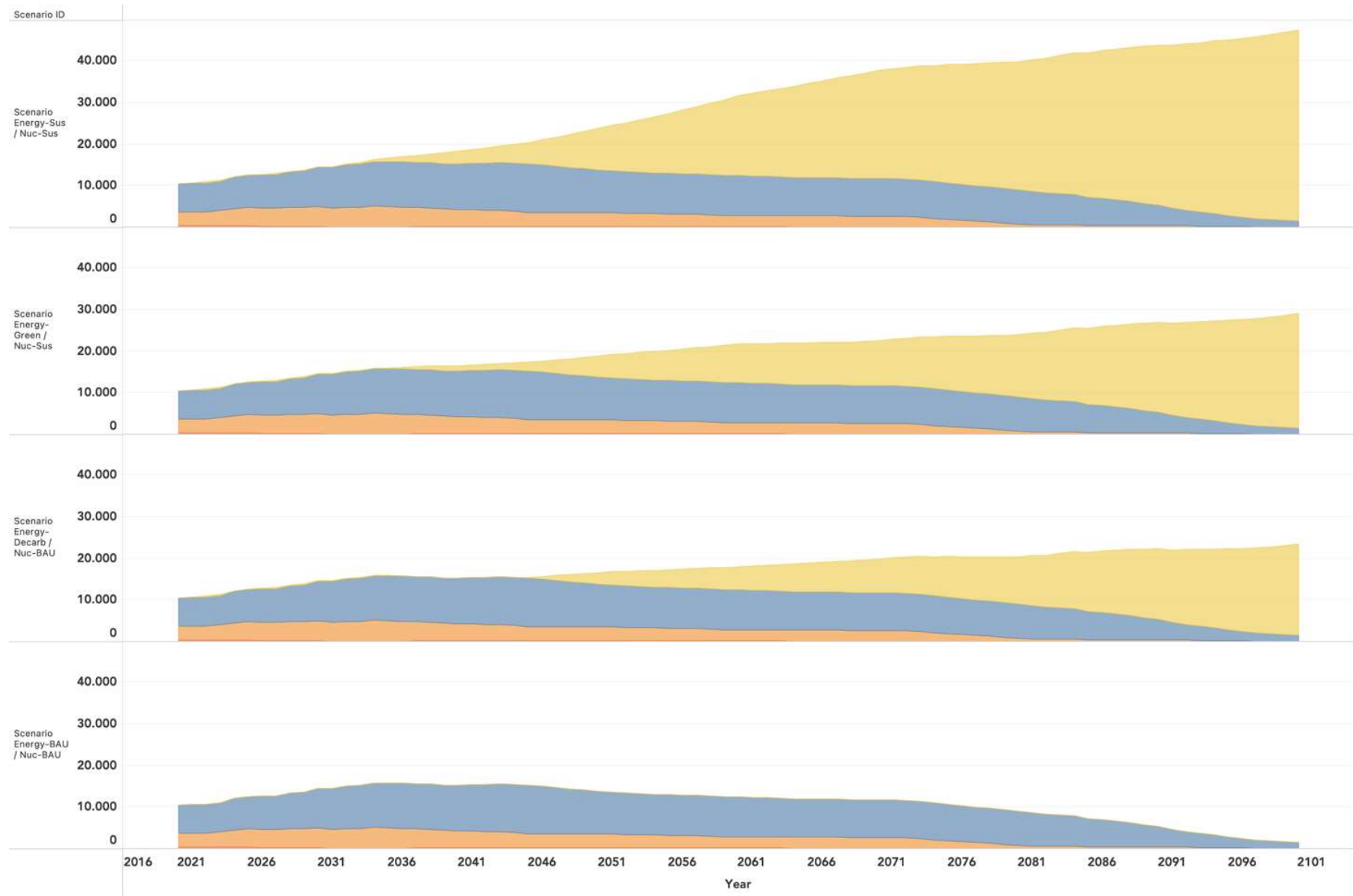


FIG. 8. Amount of annual UNF arising in scenarios.

5. CONCLUSIONS

The prospected growth of nuclear energy will go associated with a growth in the amount of UNF to be responsibly managed. The nuclear industry has done so since the early days of nuclear energy use and will continue doing so appropriately, deploying mature and safe options for such UNF. We do not lack options for such UNF management neither technologically, nor regulatory wise, nor from an economic perspective as options using reprocessing and recycling are already proven today where other more advanced fuel cycle options may become so around mid-century. Though, to truly deliver on, for instance, ‘tripling’ the nuclear energy use worldwide, we will need to ensure a strategic industrial look on the fuel cycle development using our current fuel cycle facilities at best, transitioning towards more advanced fuel cycles keeping the fuel cycle costs competitive while derisking the back end and radioactive waste management liabilities for nuclear energy users. This especially demands an international perspective given the economic interest to mutualize such nuclear fuel cycle investments while providing tangible paths towards an even better circular economy for all, including nuclear energy in their sustainable energy future.

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JRC-EURATOM FORESIGHT: ANTICIPATING THE FUTURE CHALLENGES OF SPENT NUCLEAR FUEL MANAGEMENT

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Extended Abstract

The management of spent nuclear fuel (SNF) is a critical issue that requires strategic foresight to anticipate future challenges and ensure the safety and sustainability of nuclear power. The European Commission's Joint Research Centre (JRC) and its Euratom Foresight initiative play a pivotal role in addressing these challenges through the provision of evidence-based knowledge and scientific underpinning for policy initiatives. This paper explores the JRC-Euratom Foresight approach to anticipating future challenges of SNF management and highlights its advantages and implementation process.

The JRC-Euratom foresight initiative

The JRC-Euratom Foresight initiative is an integral part of the JRC's activities, focusing on anticipating trends and being equipped to deal with them. By integrating strategic foresight and collaborative approaches into the design of new initiatives, the JRC aims to create a more resilient European Union (EU) capable of adapting to a changing environment, and help planning future work considering not only what is urgent today, but those issues that would be important in 10, 30 or 50 years from now. The Euratom Foresight cycle consists of five steps: scanning, distilling, the Sense-Making Workshop, the Deep Diving Webinars, and Science for Policy briefing.

Scanning

The first step in the Euratom Foresight cycle is scanning, which involves gathering relevant news articles and references provided by the scanners network and Europe Media Monitor (EMM), developed by the JRC. EMM monitors 17,000 websites, processing 450,000 pages daily in 80 languages, generating data that include comprehensive reports, objective content, concise statements, and fresh insights. Selected ideas are then stored in the dedicated Euratom Foresight knowledge base, like news analysing the viability of Blockchain-Based Nuclear Power Plant Management Systems, or the Oklo plans for using a fast neutron reactor as a source of carbon-free energy.

Distilling sessions

In the second step, collaborators with different professional profiles and backgrounds are asked to review the captured ideas and point out the most interesting ones on the website. Comments and observations are welcome, and in the distillation session, those ideas identified as the most significant are discussed to identify new topics or trends emerging from these conversations, which are also added to the knowledge base. One of the identified topics has been the circular economy applied to the nuclear industry, with emerging trends in research looking to recycle rare earth elements, radioisotopes, and precious metals from nuclear waste. Related with this identified trend, nowadays there is an exploratory research project ongoing at JRC, working on that.

Sense-Making Workshop

The third step, the Sense-Making Workshop, serves as a platform for participants to reflect on the most relevant ideas and technologies. Each scenario, the group proposes the main threats and opportunities, enabling the anticipation of potential threats and opportunities. The resulting ideas are later documented in the annual report.

Deep Diving Webinars

The JRC organizes open, live-streamed webinars featuring invited experts to delve into the future implications of various nuclear technological developments. To date, six deep dives have been conducted, exploring topics such as IAEA Drivers 2057³, nuclear power for space exploration, and floating nuclear reactors.

Science for Policy briefing

The last step in the Euratom Foresight cycle is the Science for Policy briefing. Concise two-page Science for Policy briefs are published at the JRC Publications Repository to enhance accessibility of key topics for a wider audience. Recent years have featured documents on Nuclear Hydrogen for Steelmaking and Nuclear Power in Space.

Since 2017, the yearly report aims to make an innovative analysis of potential future developments in the nuclear technology sector within the EU. The reports delve into key trends that may shape the industry, project potential threats and opportunities, and highlight critical questions that warrant further research and exploration. The report underscores the value of monitoring and adaptation in the face of evolving challenges and opportunities in the nuclear technology landscape.

Foresight advantages

The JRC-Euratom Foresight initiative offers several advantages, including early identification of opportunities and risks, the development of a strategic vision, design milestones and roadmaps in technology, improved decision-making, collaboration between different departments and professionals, and increased adaptability to a changing environment.

Conclusion

The JRC-Euratom Foresight initiative is a robust and collaborative approach to nuclear technology-related foresight within the JRC. By leveraging a combination of digital tools and human expertise, the JRC is well positioned to identify and evaluate innovations with transforming potential for the nuclear sector. As a result, the Foresight strategy contributes to the development of sound and evidence-based policies that promote sustainable growth and development in the EU.

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³ https://media.superevent.com/documents/20230330/752bb95d23a564987081664a7d0a6468/final_driversdeck.pdf

UPCYCLING NUCLEAR FOR CLIMATE

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Extended Abstract⁴

HEXANA in a nutshell

HEXANA is a new French startup committed to the design and development of an innovative small modular sodium fast reactor (AMR type, Advanced Modular Reactor). The power of this Generation IV reactor is 400 MW(th) and the HEXANA system provides two reactors associated with a thermal storage unit offering flexible power delivery in response to the needs of its customers (electricity and/or heat) for industrial process needs. HEXANA integrates design options offering high guarantees from the point of view of safety, relying in particular on passive safety devices. HEXANA is primarily targeting the decarbonization of energy-intensive and highly greenhouse gas-emitting industrial processes, with the combined production of heat and electricity, bases for the production of hydrogen or synthetic fuels. The sodium cooled fast reactor (SFR) heat (500°C) gives access to all the amenities needed to defossilize our economy: steam, hydrogen, CO₂ capture, synthetic fuels, green steel, chemical molecules, fresh water by desalination, ammonia, fertilizers, etc. HEXANA select the SFR technology also as part of a circular economy by using available nuclear materials: depleted uranium and plutonium from PWR spent fuel. This choice avoids any dependency on the import of uranium and offers a strategic advantage in terms of sovereignty and sustainability. With the SFR technology, HEXANA produces very low carbon energy estimated at 2.5 gCO₂/kWh, which is a key asset.

HEXANA fuel cycle goals

The use of a SFR meets a triple challenge: the reuse of plutonium from PWR spent fuel, the reduction of dependence on uranium imports and the minimization of Long Lived Radioactive Waste (LLRW) to be stored. HEXANA offers a SFR capable of meeting these challenges.

A major challenge is that of plutonium from PWR spent fuel, which would be by far the largest contributor to LLRW if it were not valued as a resource. It is reused once in France with MOX utilization in some of EDF PWRs. However, the inevitable degradation of the isotopic vector requires having SFR to sustainably reuse plutonium and stabilize its inventory on French soil, in quantity and quality. As a reminder, the current French fleet accumulates 120 t/year of spent MOX fuels. HEXANA therefore aims to be able to valorize used MOX, in support of ad hoc upstream and downstream industrial sectors.

The second challenge is that of the uranium resource and its enrichment. Even if the known reserves, the diversity of suppliers and the current tension on the market do not suggest a real surge in prices in the short term, we can note a tripling of the price of uranium since the beginning of 2020 in the wake of other raw materials. These economic arguments remain relative for the moment: France has large stocks, a diversity of suppliers and the impact of the cost of U on the price of MWh is low. However, if a rapid and massive nuclear renaissance were to take place, tensions on the U market, or even on Pu stocks, could increase more quickly than the current rate of development of Fast Reactors. At the current rate, U stocks provide 100 to 150 years of resources. However, in the event of a global desire to achieve Net Zero 2050 thanks in part to nuclear power, tensions could appear as early as the middle of the century. The issue remains geostrategic in the medium term (energy sovereignty) rather than a real short term challenge.

⁴ More information on the HEXANA design can be found in IAEA Advanced Reactors Information System (ARIS): https://aris.iaea.org/Publications/SMR_catalogue_2024.pdf

It should also be noted that the equivalent CO₂ emissions of the current nuclear kWh are 50% due to uranium extraction and enrichment activities. A SFR with a closed fuel cycle can therefore reach an ultra low carbon energy supply, up to 2.5 gCO₂/kWh, which is unbeatable.

HEXANA fuel supply and spent fuel management

In terms of core physics, it remains undeniable that plutonium from spent MOX fuels and depleted uranium from enrichment are materials that can be used in SFR and therefore in HEXANA reactors.

More specifically, HEXANA's positioning for the fuel cycle is based on the French feedback:

- MOX fuel with depleted U and Pu from PWR, with Pu content between 20 and 28%;
- Oxide fuel: good properties under irradiation, good operating feedback and compatibility with hydrometallurgical reprocessing;
- First of a kind (FOAK) starting with MOX from Pu ex-UOX and transitioning as soon as possible to 100% Pu ex-MOX cores according to industrial manufacturing possibilities;
- Objective to participate in the stabilization of the French plutonium inventory;
- HEXANA spent fuel has to be stored on the reactor site to be cooled during a couple of years before transportation to La Hague reprocessing plant. The feasibility of the reprocessing of SFR spent fuel has been demonstrated with Phenix. R&D is still needed for the industrialization of the process in case of a major deployment of fast reactors.

In the longer term (>2050), SFR technology offers different choices:

- Maintain a symbiotic PWR/SFR fleet, with SFR consuming the Pu coming from the PWRs;
- Move towards a transition from PWRs to isogenerator SFR (the HEXANA core can be isogenerator by adding a fertile crown);
- Develop higher power SFR for breeding or transmutation of americium.

HEXANA is well within the logic of engaging the closing of the fuel cycle. HEXANA has initiated discussions with Orano on both the manufacturing and reprocessing of its fuel.

DEPLOYMENT OF A MODERN FUEL RECYCLING FACILITY

The favourable economics for recycling American used nuclear fuel

(Paper ID91)

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Abstract

Rising demand for nuclear power plants to support the clean energy transition, combined with the importance of managing used nuclear fuel comprehensively and responsibly over its entire lifecycle, presents a paradigm shift for the deployment of modern recycling technologies. Although back end fuel processing was envisioned to become a key component of the complete nuclear fuel cycle, its widespread implementation has been postponed in the United States of America. Resistance to proliferation has been a contributing factor, but the primary underlying cause has thus far been the absence of a strong financial case for implementation, in a historical environment of relatively low cost uranium ore and enrichment services. However, recent technological advancements, industrial deployment activities, and macro geopolitical changes have fostered the opportunity to continue this mission, driven by natural market forces without the need in some cases for substantial, nationally subsidized funding. Considering potential near future, commercial deployment of fast spectrum reactors, particularly those using metal-form high assay low-enriched uranium (HALEU) fuel, the cost to produce uranium–transuranic TRU bearing fuel using fissionable material recovered and recycled from existing used fuel inventories can potentially be lower than the cost to produce HALEU based fuel for these reactors from fresh uranium ore. This new cost effective optionality being added to the fuel supply chain — of modern, secure, environmentally conscious used fuel recycling combined with actinide burning fast reactors — can serve to supercharge decarbonization via unsubsidized market forces. Pursuing the deployment of recycling to capture the tremendous energy reserves in used fuel offers comprehensive fuel cycle benefits while also bolstering and diversifying the fuel supply for advanced reactors and reducing repository burden. The paper will present an integrated technoeconomic analysis of the modern recycling and enrichment value chain for metal fuelled fast reactors, including a comparison of fuel sourced from uranium ore versus from recovered material, using a normalization of reactor neutronics performance.

1. BACKGROUND AND CONTEXT

The dawn of the nuclear age foresaw the importance of the development and deployment of the means to utilize nuclear fuel to its full potential, to include creating new fissionable material from unenriched and depleted uranium stocks. Reactors operating with fast spectrum neutrons (i.e. fast reactors) and fuel recycling were key components of that implementation. Some of the original power reactors were of a fast spectrum design, including the Experimental Breeder Reactor I [1].

For a multitude of reasons, that momentum toward advancement in fuel utilization and enhanced stewardship of used nuclear fuel was lost in the USA. Extensive uranium deposits were identified, naval reactor programmes zeroed in on light water cooled and light water moderated thermal spectrum reactors, and arms control efforts discouraged progress in the area of recycling [2].

A casualty of these global technopolitical shifts during the latter half of the 20th century was the fast reactor. Measured research programmes did continue in the major nuclear countries including the USA, France, Russian Federation, Japan, and India, with test and prototype reactors built in all; however, most of these programmes fought budget challenges and political pressure toward closure. Large scale fast reactors were built in a number of countries, including Japan and France which are particularly notable as they are countries that have large-scale commercial nuclear power programmes but minimal or no uranium deposits.

As the first decades of the 21st century commenced, the new spectre of climate change came to the forefront of conversations about energy policy throughout the world, particularly in the West. This brought about a compounding interest in deploying renewable energy, particularly wind and solar.

In the early 2020s, a confluence of events occurred that shifted many policymakers' mindsets regarding energy security, tending also to recalibrate their priorities and their plans. Most notably, in February 2022, Russian Federation invaded Ukraine. Almost since the fall of the Soviet Union, Russian Federation had increased its exports of oil and natural gas. Their unprovoked invasion of a sovereign, Western friendly nation earned them toxic status in the view of most nations, resulting in many of their oil and natural gas customers phasing out purchases. This reduction in supply put positive pressure on pricing, sending energy prices upward in most of the world. The key lesson learned from this by many world leaders was that they each need to take more nationalistic responsibility for their energy security. A number of nations, aware of the challenges of operating a large scale grid with non-dispatchable renewable generation assets, enacted initiatives to create or increase their nuclear generation capacity [3].

Rising demand for new fission power plants to support clean energy transitions across the USA, combined with the importance of managing used nuclear fuel comprehensively and responsibly over its entire lifecycle, presents an environment that enables the deployment of advanced recycling technologies.

New fission power plants employing advanced fast reactor technologies have the potential to deliver economic improvements, enhanced safety characteristics, modernized business models, and the flexibility to provide either continual baseload or load following clean power to the grid, to 'behind-the-meter' customers, or to a dynamic combination of the two.

The majority of these in-development fission power plants use low-enriched fuel, enriched to between 5% and 20% U-235, also referred to as high assay low enriched uranium (HALEU). Some of these new plants are referred to as advanced reactors, spanning various coolant technologies other than light water, such as gas cooled, molten salt cooled, and liquid metal cooled. A further subset of these advanced reactors are fast reactors.

Fast reactors are a significant focus of advanced reactor development due to their performance benefits, including offering the potential for significant improvements in fuel utilization, when paired with recycling. They are also quite tolerant of fuel impurities and variations in fissionable material composition, including being compatible with fuel that contains a spectrum of transuranic actinides. This combination of growing demand for advanced reactors, a growing demand for clean electricity, a distinct focus on deploying nuclear systems with positive economics as a key objective, and the fuel flexibility of fast reactors, lays the foundation for a paradigm shift in the economics of fuel recycling, particularly in the USA [2].

2. FUEL RECYCLING

The initial technology used to separate constituents of irradiated nuclear fuel was a chemical stripping process conducted first by Glenn Seaborg at Berkeley, USA in 1942. In a follow on period of only about 2 years, this process was ramped from the microgram scale to the kilogram scale, enabling deployment of the initial defence production reactor facilities at Hanford. Over the next 2 decades, this evolved into the plutonium uranium extraction (PUREX) process, which, to the present, is the de facto standard process for separating near-pure plutonium. Over time, other aqueous based variants have been developed that are similar in nature to PUREX.

Commercial-scale (>100 t/year) commercial fuel reprocessing operations over the last several decades have all utilized aqueous based methods [2], producing output products of isolated uranium and isolated plutonium, among other streams. The nature of these processes has historically dictated a large scale facility and an accordingly large operational staff.

Additionally, in cases where the output products were to be used to fabricate recycled fuel for power reactors, those power reactors were generally of a thermal spectrum, oxide fuel design, necessitating specific fissionable

nuclides be isolated for use in fabricating mixed oxide fuel (i.e. MOX). Due to the low thermal cross-section of certain nuclides such as U-236, Pu-240, and Pu-242, as well as other factors, an unlimited closed fuel cycle (i.e. multirecycling) for a fleet of thermal reactors presents some practical barriers to implementation [4, 5, 6], and thus the material extracted to make MOX fuel would generally be burned in just one or perhaps two additional cycles.

In parallel, a wholly different used nuclear fuel recycling technology was discovered and is under development: pyroprocessing. By the nature of its properties, this alternate recycling method was more suitable for reactors using metal fuel [1]. Led by Argonne National Laboratory, research evolved the technology, and experience was gained through the deployment of a pilot scale facility at Argonne-West (now Idaho National Laboratory), paired with the Experimental Breeder Reactor II (EBR-II) sodium fast reactor. This effort was further enabled by the Integral Fast Reactor programme, which ran from approximately 1984 through 1994 when it was shut down [1]. Small scale research and testing continued unabated, further enabled by the Global Nuclear Energy Partnership (GNEP) programme, which was initiated in 2006 but also later cancelled.

Pyroprocessing, as applied for the purpose of separating selected constituents from used nuclear fuel, consists of running electrochemical reduction and/or oxidation reactions at elevated temperatures in an inorganic electrolyte. The absence of moderators, organic chemicals, and liquid process effluents allows for a compact, lower hazard, environmentally friendly process, when compared with the baseline PUREX facilities [7].

At the time of this writing, the technology has been advanced to an operational level of maturity at both lab scale and pilot scale. Pilot pyroprocessing operations at the Idaho National Laboratory continue, for the purpose of recycling used EBR-II fuel. Research and development have been conducted that have refined the technology in areas including process control, electrolyte assay, fission product waste forms, and electrode materials. Research work continues, on these areas and others, primarily in national laboratories of the USA and other nations.

3. FAST REACTORS AND FUEL

Oklo is a USA company that stands apart from the vast majority of other modern, Western nuclear developers, as it is developing reactors with the intent to build, own, and operate them, with the goal of earning revenue through sales of energy via power purchase contracts. Due to this vertically integrated business model, Oklo is focused on a comprehensive technoeconomic solution, considering aspects that in the legacy commercial nuclear industry would be within the purview of the operating utility more so than the reactor developer: construction and operation cost, as well as fuel cost and availability. In consideration of these factors, as well as potential customer demand and deployment timeframe, Oklo intends to use a sodium fast reactor design, of 15 to 50 MW(e), with metal fuel. Other commercial entities in the USA and other Western nations have also started initiatives to commercialize fast reactors, while Russian Federation and China continue to proceed with their own state sponsored programmes.

Fast reactors fuelled with uranium require a higher level of enrichment than that of uranium fuelled thermal reactors, at levels nearing 20%. This increased level of enrichment, although still classified as low enriched uranium (LEU), has been christened high assay low enriched uranium (HALEU). To produce HALEU, either existing high enriched uranium can be down-blended by mixing it with depleted or natural uranium, or it can be enriched from natural or LEU, generally using a centrifuge cascade while in uranium hexafluoride form.

This current resurgence of fast reactor deployment interest is occurring somewhat in advance of the rollout of HALEU production capacity, as well as during a ramping upwards of global uranium spot prices. Although these are likely temporary factors that are expected to resolve themselves through natural market forces, they can serve as a cautionary tale that illustrates the impact of geopolitical forces on raw material pricing and availability.

However, neither thermal reactors nor fast reactors are limited to using uranium to produce energy through fission. A multitude of nuclides in the actinide series can be fissioned by thermal spectrum neutrons, and a considerably larger group can be fissioned by fast spectrum neutrons.

Somewhat fortuitously, though, a selection of these fissile nuclides is present in used nuclear fuel. Similarly to certain nations with deployed commercial nuclear programmes, but without implementation of either commercial used fuel recycling or an active geological repository, the USA has a substantial inventory of fuel in temporary storage. As a realization of the 1970s USA policy decision to operate a once-through fuel cycle for commercial power reactors, the 1982 Nuclear Waste Policy Act assigned responsibility to the USA Department of Energy for the collection and disposal of used commercial fuel [8]. Decades of political dysfunction, combined with a lack of focus on community consent for repository siting, have led to the present impasse — as well as over 90 000 tonnes (heavy metal mass) of USA used nuclear fuel in interim storage. The fissionable energy content in that used fuel, when unlocked using recycling and fast reactors, could meet the present day electricity needs of the USA for over 100 years [9].

4. OKLO DEPLOYMENT

Many benefits could potentially be realized through the deployment of used nuclear fuel recycling in the USA: fuel material can be recovered for reuse, waste volumes can be reduced, surplus uranium can be recovered, certain long lived radiotoxic nuclides can be consumed through fission, and specific radioisotopes with commercial demand can be extracted.

Oklo has set upon the mission to license and deploy a commercial USA facility designed to recycle used nuclear fuel, recovering certain fissionable constituents for their use in manufacturing new fuel for Oklo's planned fleet of fast reactor powerhouses. This first-of-a-kind commercial recycling facility intends to leverage the pyroprocessing technology and the lessons learned over decades of fuel cycle development and operation, while taking the approach of intrinsically integrating security, material safeguarding, and environmental stewardship.

Since the Oklo recycling programme is a commercial undertaking, conducted almost entirely using private, non-governmental funding, the scope of the programme can be focused and limited to support the needs of the business — namely, production of fuel material that is expected to increase the optionality and economy of its fuel supply chain. Oklo is evaluating the deployment of a commercial scale USA facility designed to take used nuclear fuel from the existing USA commercial thermal reactor fleet, and recycle it to generate streams of uranium, uranium combined with mixed transuranic (TRU) material, and fission products. Oklo intends to use the pyroprocessing technology, scaled up to a capacity of hundreds of tonnes of input material per year. The processing operations are designed to be conducted inside an inert atmosphere hot cell, without direct human intervention, by automated handling equipment. The sequence of unit processes is the following:

- (1) Fuel receipt and offloading from transport casks;
- (2) Deconstruction of fuel assemblies;
- (3) Decladding of the used fuel meat from the rods;
- (4) Reduction of the oxide-form material to metal;
- (5) Electrorefining to extract uranium metal, and mixed transuranic metal diluted with uranium metal;
- (6) Processing of cathodes to remove entrained salt, and casting of extracted metal into ingots.

Additional supporting operations should occur in parallel, including salt cleanup to remove fission products and other contaminants, off-gas separation, and immobilization of waste into engineered forms. Non-destructive, and in some cases destructive, assay is conducted for material accountancy and quality control purposes.

A feature of pyroprocessing is that throughout all the main processes, when temperatures are reduced, the materials freeze into a solid form. In contrast, aqueous based separation technologies require large volumes of

liquid that form radioactive solutions that have to be stored in tankage. This alleviates risk to the environment from a source term release. Environmental damage caused by legacy facilities such as those at West Valley can be prevented through the utilization of the pyroprocessing method over legacy, aqueous based alternatives.

High Level Waste (HLW) and greater than Class C waste are immobilized into one of a few differing forms. These forms are loaded into canisters that are sealed for onsite storage, awaiting collection by the USA Department of Energy. The volume of HLW is expected to be reduced through this recycling operation, and its radiotoxicity reduced, notably through the removal of virtually all the long lived plutonium isotopes. Low level waste will be packaged and shipped for near surface disposal at one of the commercially operated USA sites.

A separate fuel fabrication facility is intended to be operated by Oklo, to produce fast reactor fuel assemblies from the uranium and TRU material extracted from the used fuel. This process is conducted in a hot cell, due to the gamma and spontaneous neutron emissions from some of the nuclides in the transuranic mix, and from contamination of the material with latent fission products. Once completed, these fuel assemblies could be shipped to Oklo powerhouses.

The primary hazards likely to be present in the Oklo recycling facility operation are fire and criticality. The fire hazard is present primarily due to the pyrophoric nature of many of the metal form materials. This hazard is minimized through inerting the hot cell atmosphere. Criticality has to be managed whenever handling fissile materials, through control of geometry while in solid form, container geometry and capacity limits for molten salt process modules, and non-presence of moderating materials. Redundant sensors and systems manage these conditions as part of the facility control system.

Physical protection and material safeguarding are key design considerations, and for this reason the entire facility is designed to optimize these objectives. Many key features are to be intrinsically integrated into the facility design to induce delay of any attempted breach, maximize detectability of material being diverted from a control area, and prevent unauthorized removal of materials or waste.

5. INTEGRATION INTO THE FAST REACTOR FUEL CYCLE

When implementing the recycling of used nuclear fuel, it is crucial to have sufficient, reliable offtake paths for the recovered products. For a commercially focused recycling operation, the net of the offtake revenue and the operational and distributed capital costs need to be positive.

As discussed earlier in the paper, utilizing an aqueous process to extract plutonium and uranium from thermal power reactor fuel, which is used to produce MOX fuel for those thermal power reactors, presents certain challenges, both technical and economic [2]. Firstly, these facilities have a large scale and cost, due to this aqueous methodology necessary to separate plutonium from other transuranic nuclides that are largely non-fissile by thermal spectrum neutrons. Secondly, due to progressive buildup of non-fissile uranium and plutonium isotopes (particularly U-236 and Pu-240) and increase in decay heat and increased spontaneous neutron emission, the recovered material is generally only used as MOX once (i.e. single-recycling) [10].

The pyroprocessing facility described in this paper is expected to have a considerably lower construction and operation cost compared with the reprocessing plant from the reference fuel cycle of using aqueous based reprocessing to produce single-recycled MOX for use in thermal reactors [10]. Additionally, the neutronics of fast reactors are expected to allow the recovered material to serve as fuel multiple additional times (i.e. multirecycling), with blending to optimize core performance [10]. The capability to recycle fast reactor used fuel, both HALEU based and recycled transuranic based, is intended to be added to the licence and operation of the facility in the future; this further bolsters the economics.

6. FEEDSTOCK CONSTITUENTS

Presently, the fuel used in the domestic fleet of commercial thermal spectrum light water reactors (LWRs) almost entirely comprises mined, enriched uranium. Once reaching the targeted burnup level, typically after use in a reactor for 4.5 to 6 years, the fuel is then put into storage, with no specific intention of recycling or reuse [11]. This used LWR fuel comprises ~1% transuranic (TRU) material, some nuclides of which have a long radiotoxicity lifespan, of more than 100 000 years. Although these long lived nuclides constitute only a small portion of the used fuel — when the used fuel is left in its composite form, it results in the entire mass needing to be isolated safely throughout the radiotoxicity lifespan of the long lived nuclides.

Incorporating used fuel recycling within the fuel cycle for LWRs such as pressurized water reactors (PWRs) and boiling water reactors, or other thermal reactors such as pressurized heavy water reactors, requires high purity separations of the fissile components in used fuel, which necessitates expensive, large scale facilities, since non-fissile nuclides have to be within certain limits prior to its use in recycled fuel. LWRs are also limited to conducting only a low number of recycling passes due the neutronic challenges introduced by the buildup of actinides that are non-fissile in the thermal neutron spectrum. Furthermore, the use of recycled fuel should be economically competitive when compared to using fresh fuel, a challenging prospect for LWRs currently using fresh, low enriched uranium (LEU) enriched to less than 5%, which for an extended period has cost less than \$2,000/kg [2], although the spike in early-2024 spot prices has the potential to apply upward pressure to that LEU pricing.

The feedstock used fuel from thermal reactors is purposefully selected based on its properties, primarily initial enrichment, burnup, and decay time. In the USA, this material is currently being discharged at a rate exceeding 2,000 tonnes annually, so considerable domestic recycling capacity will need to bring online just to reach production parity [2].

7. FAST REACTOR FUEL

Unlike LWRs, fast reactors can accommodate fuel with a wide range of actinide vectors, as well as impurities, with little effect on reactor performance. Additionally, fast reactors fuelled with uranium will generally require HALEU, often enriched above 12%, and in many cases to near 19.75%. As of early 2024, there is not yet large scale USA domestic HALEU enrichment capacity; international supplies are limited, and in some cases their acquisition is geopolitically complex. Furthermore, producing 1 kg of 19.75% HALEU metal requires between 50.7 SWU and 41.4 kg of U₃O₈ at 0.15% tails, and 41 SWU and 50.1 kg of U₃O₈ at 0.25% tails (see Table 1). This naturally leads to more expensive fuel costs for HALEU compared to LWR LEU fuel, of approximately \$7,000/kg or greater, projected for HALEU at commoditized production scales.

TABLE 1. COMPARISON OF SWU AND U₃O₈ FEEDSTOCK REQUIRED TO ATTAIN 1 kg OF U AT VARIOUS ENRICHMENT LEVELS

	4.95%-enriched (0.15% tails)	4.95%-enriched (0.25% tails)	19.75%-enriched (0.15% tails)	19.75%-enriched (0.25% tails)
SWU	10.0	7.8	50.7	41.0
U ₃ O ₈ (kg)	10.2	12.1	41.4	50.1

The ability of fast reactors to use flexible fuel compositions, such as those produced from advanced recycling technologies, has long been appreciated. This has helped spur decades of research and development into advanced recycling technologies that can inherently match fast reactor fuel utilization attributes with advanced recycling technologies, such as pyroprocessing.

8. PYROPROCESSING

Pyroprocessing is an advanced technology for recycling that employs electrometallurgical techniques to separate used fuel constituents such that they can be reused. At a high level, pyroprocessing based recycling entails the following steps:

- (1) Disassembly of the used fuel from its fuel assemblies, and in some cases removal of cladding;
- (2) If applicable, the reduction of the oxides to metal;
- (3) Applying an electrical current between anodes and cathodes in an electrolyte to separate TRU (e.g. neptunium, plutonium, americium), uranium, and fission products from each other, in targeted ratios.

Uranium combined with mixed transuranics (U/TRU) is extracted from electrorefining as a solid. Uranium metal is extracted separately. The recovered U/TRU and uranium material can be used to produce metal fuel for fast reactors by thereafter conducting any needed down-blending and alloying, followed by fabricating the end fuel product. Often zirconium is used for this alloying, to produce U–TRU–Zr metal fuel.

Used LWR fuel (ULF) generally contains 0.5-2.0% TRU, 92-95% U-238, 0.5-2% U-235, and 3-5% fission products [11]. The specific actinide vector of ULF varies based on a variety of factors, primarily the initial enrichment and burnup. As LWR fuel performance has improved over the last 50 years, burnup levels have trended upward. Additionally, recent initiatives to implement 24 month refuelling cycles at PWRs have initiated programmes to increase initial enrichment and burnup levels even further. Example actinide compositions of ULF based on burnup are presented in Table 2.

TABLE 2. ACTINIDE WT% COMPOSITIONS AT DISCHARGE OF 4.5%-ENRICHED ULF AT SELECTED BURNUP LEVELS

	20 MWd/kg	30 MWd/kg	45 MWd/kg	60 MWd/kg
Np-237, of TRU	2.850%	3.830%	5.006%	5.802%
Pu-238, of TRU	0.437%	0.938%	2.014%	3.340%
Pu-239, of TRU	73.246%	64.452%	54.204%	46.557%
Pu-240, of TRU	13.900%	16.583%	18.979%	19.983%
Pu-241, of TRU	8.280%	11.227%	13.437%	13.958%
Pu-242, of TRU	1.005%	2.222%	4.433%	6.718%
Am-241, of TRU	0.143%	0.272%	0.415%	0.472%
Am-242m, of TRU	0.003%	0.008%	0.015%	0.019%
Am-243, of TRU	0.093%	0.316%	0.934%	1.781%
Cm-242, of TRU	0.026%	0.070%	0.152%	0.221%
Cm-243, of TRU	0.0000%	0.001%	0.005%	0.009%
Cm-244, of TRU	0.014%	0.077%	0.377%	1.042%
Cm-245, of TRU	0.001%	0.004%	0.028%	0.099%
All TRU, of total heavy metal	0.764%	1.031%	1.351%	1.604%
U-234, of U	0.038%	0.034%	0.028%	0.022%
U-235, of U	3.019%	2.309%	1.473%	0.880%
U-236, of U	0.388%	0.523%	0.667%	0.748%
U-238, of U	96.556%	97.134%	97.833%	98.350%
All U, of total heavy metal	97.158%	95.858%	93.994%	92.200%

9. FAST REACTOR NEUTRONICS ANALYSIS

Many of the TRU nuclides present in ULF are fissionable in a fast reactor. Furthermore, many TRU actinides have higher reproduction factor (η) values (see Eq. 1) compared with the η for U-235 in a fast reactor. That

means that TRU fuel is more reactive than HALEU on an atom-by-atom basis. These characteristics make TRU bearing fuel superior to HALEU from a reactor core physics perspective. This allows fast reactors to achieve comparable performance with fuel containing less TRU wt.% compared with the required U-235 wt.%. For example, SERPENT analyses of a sodium cooled fast reactor using 19.75% enriched U–Zr fuel and various TRU concentrations of U–TRU–Zr for the same fuel dimensions were performed. The results show TRU concentrations between 11 wt.% to 16 wt.% offered comparable reactivity to that of a 19.75% enriched U–Zr design. To delineate nomenclature, TRU-20 represents TRU produced from typical PWR used fuel irradiated to 20 MWd/kg, TRU-30 represents TRU produced from typical PWR fuel irradiated to 30 MWd/kg, and so forth. See results presented in Fig. 1.

Equation 1. Reproduction Factor:

$$\eta = \sigma_f * \left(\frac{\nu}{\sigma_a}\right) \tag{1}$$

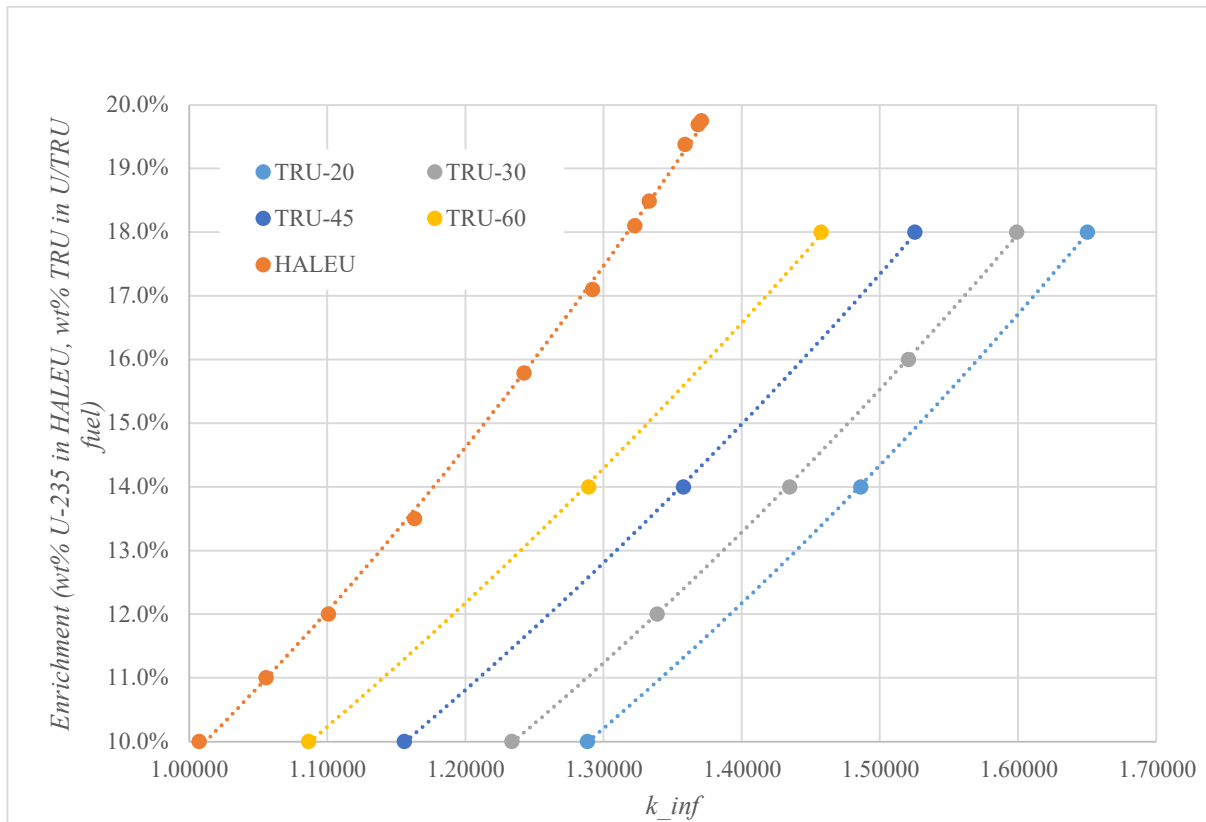


FIG. 1. Reactivity comparison between selected U/TRU and HALEU compositions.

Based on these analyses, TRU bearing fuel is significantly more reactive than HALEU. TRU recycled from lower burnup ULF is more reactive than TRU recycled from higher burnup ULF, but higher burnup ULF yields significantly more TRU per kilogram of used fuel recycled. See Table 3.

TABLE 3. TRU MASS RATIO AT DISCHARGE REQUIRED TO MATCH REACTIVITY OF 19.75% HALEU FOR SELECTED ULF SOURCES OF TRU

	HALEU	TRU-20	TRU-30	TRU-45	TRU-60
Required mass ratio for equivalent reactivity	19.75%	11.56%	12.67%	14.33%	15.89%

Weighting the reactivity by the yield of TRU for various sources of ULF according to their burnup yields the unitless data presented in Table 4, wherein higher values reflect better overall performance. The data presented in Table 4 illustrates that although TRU bearing fuel produced from higher burnup ULF may be less reactive than TRU bearing fuel produced from lower burnup ULF, it is offset by the greater quantity yield of TRU from higher burnup ULF. Notwithstanding other factors, this means that higher burnup ULF can be more economically positive to use as feedstock for recycling, which complements LWR used fuel management strategy today, since older, lower burnup fuel is often already in dry cask storage systems, while newer, higher burnup fuel is often still in wet storage pools. Transferring that more economically positive, newer, higher burnup fuel directly from wet storage to recycling provides economic savings by avoiding dry storage campaign costs and by avoiding use of dry storage space, while opening up more storage rack space in wet storage pools.

TABLE 4. REACTIVITY CONTRIBUTION COMPARISON FOR SELECTED ULF SOURCES OF TRU, AT DISCHARGE

	TRU-20	TRU-30	TRU-45	TRU-60
Reactivity contribution (unitless)	0.0675	0.0840	0.0989	0.1076

10. PRIOR PYROPROCESSING DEPLOYMENT AND OPERATIONAL COST ESTIMATES

In 2018, Argonne National Laboratory (ANL) completed and published a conceptual design and associated cost estimates for a pilot scale electrorefining facility [7]. This presented a thorough design of a pilot scale facility sized to process 100 tonnes of ULF per year. The cost estimates that were generated jointly by ANL and Merrick & Company, Inc. are detailed in Tables 5 and 6.

TABLE 5. CAPITAL PROJECT COSTS FOR A 100 t/YEAR FACILITY [7]

Category	Cost with Contingency (K 2015 USD)
Facility	298,649
Process equipment & support	89,534
Licensing support	6,000
Startup materials	3,431
Total	397,614

TABLE 6. ANNUAL OPERATING COSTS FOR A 100 t/YEAR FACILITY [7]

Category	Cost with Contingency (K 2015 USD)
Staffing	41,790
Materials & services	4,180
Process chemicals	579
Spare parts	120
Product & waste containers	5,472
Utilities	984
Total	53,125

The same study also presented preliminary cost estimates for a conceptual larger commercial scale facility, sized to process 400 tonnes of ULF per year. Costs for that facility are detailed in Tables 7 and 8.

TABLE 7. CAPITAL PROJECT COSTS FOR A 400 t/YEAR FACILITY [7]

Category	Cost with Contingency (K 2015 USD)
Facility	674,960
Process equipment & support	210,780
Licensing support	12,000
Start-up materials	13,730
Total	911,470

TABLE 8. ANNUAL OPERATING COSTS FOR A 400 t/YEAR FACILITY [7]

Category	Cost with Contingency (K 2015 USD)
Staffing	56,460
Materials & services	4,910
Process chemicals	2,320
Spare parts	480
Product & waste containers	21,890
Utilities	3,940
Total	90,000

11. FINANCIAL MODEL

A project pro forma model was developed to evaluate the economics of implementing a 400 t/year ULF recycling facility, to recover material to use as fuel for fast reactors. The economic model assumes a three year construction timeline, assumes cost of financing at 4.5%, and adjusted the 2018 cost projections in consideration of inflation and other factors. Additional expenses not covered in the 2018 analysis were also added, including transport, regulatory fees, and payments into a decommissioning fund.

Various ULF feeds were analysed, spanning burnup scenarios from 20 to 60 MWd/kg, and cooling intervals from 5 years to 50 years. These scenarios affect the TRU yield and ‘quality’ (or reactivity worth in fast reactors) of various ULF feedstocks. As described in the preceding section, higher burnup ULF yields more TRU, but of lower quality, while lower burnup ULF yields less TRU, but of higher quality. Based on these models and associated analyses, a 400 t/year facility is projected to produce 19.75% HALEU equivalent TRU bearing fuel material, using 60 month decayed, 45–60 MWd/kg burnup ULF feedstock, for an all-in cost of between \$5,900 and \$9,500/kg, as presented in Table 9, with the most economic case being the use of high burnup ULF, with as short a decay period at discharge as can be managed for economically optimized transport.

TABLE 9. PROJECTED ALL-IN OPTIMIZED COST OF PRODUCED 19.75% ENRICHED HALEU-EQUIVALENT U/TRU MATERIAL USING 60-MONTH DECAYED ULF

	20 MWd/kg	30 MWd/kg	45 MWd/kg	60 MWd/kg
Projected U/TRU cost/kg	\$12,400-\$16,800	\$9,200-12,400	\$7,000-\$9,500	\$5,900-\$8,000

In this example, the fuel assembly hardware would be compacted and disposed as low level waste[12], and the medium lived fission products would be immobilized into a waste form as high level waste (HLW), for future repository disposition.

This analysis neglects the additional potential value that could be generated by separating certain ULF constituents into components that can generate further revenue. For example, the zircaloy cladding can be recycled for use in fast reactor reflectors and as a metal fuel alloying material, and the balance of the recycled uranium, beyond what is used along with the TRU in new fuel fabrication, recycled for further use. There is also the potential to extract selected high value radioisotopes from the fission product or TRU stream for revenue sales to industrial or other applications. This analysis also does not consider any potential recycling service revenue generated from utilities or government, considering that recycling provides back end benefits ranging from volume reduction, to opening up different repository geologies, to supporting optimized form factor waste ingots suitable for alternative packaging such as those for deep boreholes. These factors will reduce disposal costs compared to a baseline case of mined-repository emplacement of complete ULF fuel assemblies in dual purpose canisters.

12. BUSINESS OPPORTUNITY

Compared to the use of fresh HALEU fuel, the use of TRU bearing fuel produced from recycled ULF offers promising economic performance, which in turn would further enhance the economic attractiveness of advanced reactors, particularly fast reactors using metal fuel. Combining a set of optimized parameters for recycling deployment and operation, including feedstock selection, recycling technology utilized, and offtake revenue, once scaled to commercial levels, has the potential to create a wholly different economic result compared with the reference fuel cycle of using aqueous based reprocessing to produce single-recycled MOX for use in thermal reactors. Pursuing recycling to capture the tremendous energy reserves in used fuel offers complete fuel cycle benefits while also bolstering and diversifying the fuel supply chain for advanced reactors. Accordingly, policy advances that better enable US private entities to deploy domestic recycling facilities will yield fruitful dividends by further allowing natural market forces to enable advanced reactor deployment and thus realize the deep decarbonization benefits provided by substantial increase in US nuclear generation capacity.

13. PATH TO REALIZATION

Pursuing the deployment of a commercial used nuclear fuel recycling facility in the USA. is not an undertaking for the faint of heart. History books outline the woeful tales of facilities unfinished, shut down early, or completed but not started up.

Oklo looks to deliberately craft a pathway to deployment and operational success through thorough, early technoeconomic analysis, with the goal of minimizing risk to siting, licensure, commissioning, and safe and effective operation. Following initial licensure and operation, Oklo believes further phased expansions can be conducted based on lessons learned from the initial phase. As of early 2024, Oklo is conducting technology development, pre-application regulator engagement, and community supported siting. Pre-application engagement serves to explore key topics collaboratively with the regulator, for the purpose of obtaining alignment prior to application submittal and licence review. Oklo targets initial recycling facility operation by the beginning of the 2030s.

14. SUMMARY

Oklo is in the process of siting and licensing, toward deploying a first-of-a-kind, privately funded, commercial US facility that will be designed to recover fissionable material from light water reactor used nuclear fuel and then process that recovered material into fresh, metal form, fast reactor fuel to be used in Oklo powerhouses. In the future, this facility is also planned to recycle used fuel from Oklo powerhouses, to be blended and reused in Oklo powerhouses.

The pyroprocessing technology Oklo expects to utilize at this planned facility has been proven over decades of engineering scale operations. Oklo intends to leverage lessons learned over several decades of fuel cycle development and operation.

This facility is designed with features that are expected to de-risk its deployment; maximize the economy of its licensure, construction, and operation; and ensure effective physical protection, material safeguarding, and environmental stewardship.

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IMAGINE – A BREAKTHROUGH NUCLEAR TECHNOLOGY OPERATING ON SPENT FUEL WITHOUT PRIOR REPROCESSING

(PAPER ID103)

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Abstract

Nuclear has to play its role in delivering net zero energy for the future. This has been meanwhile recognized by several governments and supported through the IAEA. However, this will lead to a clear increase in the amount of spent nuclear fuel (SNF) on the one hand. On the other hand, if nuclear will grow at the rate proposed during COP28 the supply of fissile material will be a problem on the longer term. With iMAGINE, we have introduced a novel, highly innovative system which is able to deliver the advantages of a closed fuel cycle system, but with all steps integrated. It is based on revolutionary ternary visions: delivering unlimited nuclear energy, zero waste nuclear and accident free nuclear integrating not only technical aspects but also the expectations of the public in a future nuclear system. The vision has been transformed into the missions, to release a factor of 100 more energy out of the existing resource, reduce the amount of waste per produced energy to 1% or lower, compared to LWR, and strategically reducing the driving forces for potential accidents as well as limiting potential consequences. To progress iMAGINE, a project plan has been developed aiming at industrial demonstration in the 2040s. The potential of iMAGINE regarding resource supply has been shown for Republic of Korea and Germany with the potential for ~300 years electricity production on SNF only. For the UK, the use of the SNF as well as of the tailings could reach ~7500 years based on the current electricity production. In the final step, the operation of a self-sustained breeding system has been demonstrated through an advanced modelling and simulation approach to investigate the long term operation demonstrating self-sustained breeding without supply of fresh fissile material. Unlike solid-fuelled reactors, iMAGINE does not require a clean fuel supply, eliminating the need for reprocessing and thus, the risk of proliferation and misuse of separated fissile materials.

1. INTRODUCTION

The iMAGINE programme [1] is an innovative approach to deliver on the aims of spent fuel management in an integrative and far reaching way. It is based on the operation of a reactor directly on spent nuclear fuel (SNF) from light water reactors without prior reprocessing. The programme is currently financed through the Royal Academy of Engineering, UK and the UK Research and Innovation.

The core of this novel approach is to integrate dealing with SNF and waste management with the energy production system, rather than operating a series of reactors dedicated for waste management [2]. The system is based on molten salt reactor technologies with very wide design objectives - delivering an optimized system for zero carbon energy production with as little environmental impact as possible. This is only possible due to the unique opportunities of highly integrated molten salt fast reactors. This technology offers the possibility to operate the reactor in an integrated manner linked with a salt cleanup system based on reverse reprocessing providing its own Pu through internal self-sustained breeding processes. Reverse reprocessing is a system which does not aim for the separation of fissile materials, instead of this, the salt cleanup will be designed to aim for fission products which prevent the reactor from long term operation. The salt cleanup system, which is in anyway essential for the long term operation of the reactor, allows for the online processing of the inserted spent fuel from light water reactors instead of requiring external reprocessing and Pu separation, as needed for the operation of other advanced reactors. In contrast to classical P&T systems with their two-tier approach – fast reactors for using the plutonium for energy production and a molten salt reactor (Russian Federation) or

an accelerator driven system (EU) as tier two burner – this innovative approach delivers on both tiers in a single integrated molten salt fast reactor.

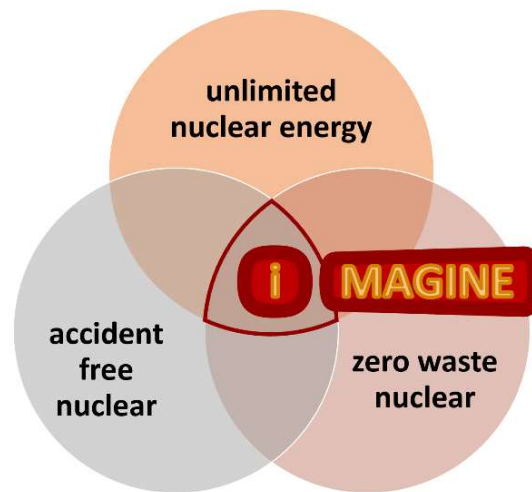


FIG. 1. The ternary vision as basis for the further development of the iMAGINE project.

The developed vision for the project, see Fig. 1, aims to deliver not only on scientific expectations, but also on the wider public demand to improve the acceptance of nuclear technologies as a basis for its future success. For this, the first social science based analysis has been delivered to understand the expectations of the public on a future nuclear system [3] which have been actively integrated into the project planning. Key points raised were: (1) potential accidents, (2) the nuclear waste issue, (3) the pollution through mining, and (4) the misuse of civil nuclear technologies for the production of weapons materials. The vision unlimited nuclear energy is transformed to the mission of achieving the aims of closed fuel cycle operation to release a factor of 100 more energy out of the already mined nuclear material like spent fuel and tailings. In contrast to traditional closed fuel cycle systems, iMAGINE allows an integrated once through operation without external reprocessing – this will allow the generation of a significant amount of energy without mining for new resources (answering public concern 3). The aim is to make already mined resources available through advanced technology development without creating proliferation issues due to enrichment, reprocessing or separation of fissile material (public concern 4). Additionally, the mission delivers a significant improvement of the resource security for all countries which have operated nuclear power plants in the past. For the newcomer countries, the option could be to start the iMAGINE system with enriched Uranium and subsequently feed the system with the tailings accumulated through the enrichment process. The vision zero waste nuclear is reflected in the mission aim of reducing the amount of waste per produced energy to 1% or lower, compared to LWR open fuel cycle operation (public concern 2). This is achieved by releasing almost all energy from the already mined material (public concern 3); this is also the part which links to the mission of energy. This has to be achieved through the consequent use of all fissile as well as fertile material and through developing reasonable strategies for the fission product removal; followed by delivering options for the management of fission products through recycling alternatives and the potential to separate waste streams along half-lives. The vision accident free nuclear is transformed into the mission of strategically reducing the driving forces for potential accidents as well as limiting the consequences. Core points are relying on a low pressure primary system, and ideally developing a low pressure energy conversion system which could deliver a higher efficiency as potential link to energy. Other important points are eliminating accidents initiators like avoiding excess reactivity, reducing the potential radiological source term of the system (public concern 1), and limiting proliferation risks, since proliferation could be seen as another kind of ‘accident’ in the nuclear fuel cycle system (public concern 4). The iMAGINE project is being pursued at the University of Liverpool in partnership with other universities and supported by the Royal Academy of Engineering (RAEng), the Department of Business, Energy, Innovation and Skills (BEIS) in the UK, now Department for Energy Security and Net Zero (DESNZ), and UK Research and Innovation (UKRI). The roadmap developed for iMAGINE is given in Fig. 2 which highlights the major stepping stones [4]. The project plan follows a comparable structure as the Russian molten

salt reactor programme with a strict, stepwise approach for development. This reduces the risk in cost and development time throughout the process required for the development of a new, highly innovative nuclear system with the demand to deliver not only the reactor, but also the required fuel cycle chemistry as well as the skills base in the UK.

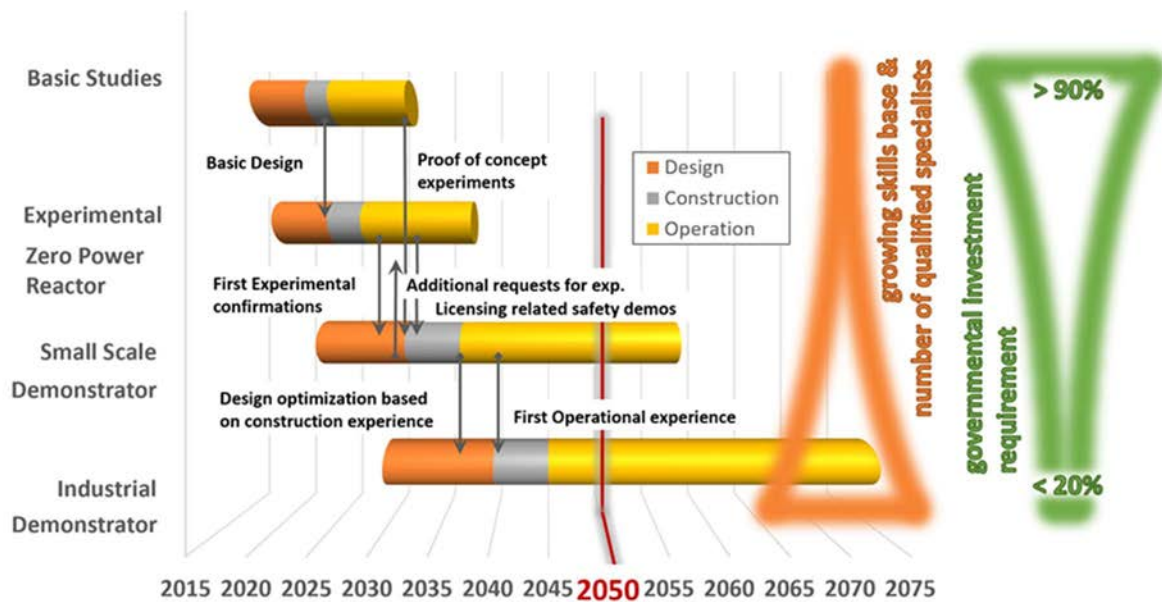


FIG. 2. Project development roadmap for the iMAGINE project [4].

As mentioned above, the core challenge and demand for this new approach is the integrated nature of the system delivering not only a reactor, but also the whole fuel cycle system at one place. This will require a close collaboration between the reactor engineers and developers on the one hand, and the nuclear chemists and the process developers on the other hand. Thus, the key for success is to deliver the fast reactor technology using molten salt fuel as well as the so-called reverse reprocessing [5], [6] to allow the online separation of fission product elements which prevent the reactor from long term operation, instead of the separation of fissile materials for new fuel production. The main advantage of this reverse reprocessing scheme will be the elimination of the nuclear proliferation issues, a problem arising from fissile material separation in classical reprocessing, as well as the completely new opportunities of the nuclear waste management possible due to the changed nature of the waste streams [7]. The required salt cleanup processes will deliver the fission products in elementary form, instead of ‘the soup’ – a mix of all fission and activation products left over for conditioning after the aqueous reprocessing. The elementary form will create well separated waste streams with various opportunities; for e. g. handling high heat producing elements in a different way than the long lived soluble fission products which are seen as critical for the long term safety of a final disposal. In addition, the elementary separated form of the fission products offers the opportunity for the reuse of some materials, e. g. noble metals and rare earth elements.

The reactor itself has the potential to be operated on a lower risk level due to the excellent inherent stability resulting from the unity of fuel and coolant, as well as due to the absence of high pressure systems significantly reducing the driving forces under potential abnormal operational conditions. The reactor start-up can be either based on plutonium, in the case it is already available in a separated form like in the UK, or it can be started based on enriched Uranium fuel, and successively fed by spent nuclear fuel from existing reactors harvesting all energy stored in the spent fuel. In both cases, it will be possible to achieve a self-sustained long term operation [8] and robust control through thermal feedback effects [9]. The operation does not require the addition of new fissile material as the fissile material will be renewed continuously and permanently stay in the reactor. The first substantial step, the zero-power reactor experiment is currently under development in the UK [10].

2. WASTE AS AN OPPORTUNITY

Meanwhile, a basic evaluation to demonstrate the opportunities and the energy resources which can be unlocked through the iMAGINE technology has been performed for three countries, considering around 100 kg of U-238 required per 1TWh For Germany, the use of only spent fuel could deliver 300 years of the full electricity production (Electricity consumption Germany, 560.55 TWh in 2022 Germany: Energy Country Profile - Our World in Data⁵) of today based on 16000 tonnes of SNF. Republic of Korea has 8691 tonnes of LWR spent fuel and 9725 tonnes of CANDU fuel as of the end of 2022 which will offer about the same outlook as for Germany (Consumption Republic of Korea 606.51 TWh per year in 2022. Republic of Korea: Energy Country Profile - Our World in Data⁶). Considering this, the slightly higher amount of SNF and the slightly better quality of the CANDU fuel (99% U-238) – we could say in a first guess, the SNF would deliver ~ 300 years of electricity for Republic of Korea – these are the resources which are stored in the country and could be made accessible through iMAGINE.

Focussing back to the UK, these potential energy resources, currently declared as nuclear waste materials, allow the following calculation. NDA data from the radioactive wastes report 2016 [11] indicate 7000 tonnes of spent fuel and 200 000 tonnes of Uranium tailings as waste. The use of iMAGINE could turn this burdensome ‘waste material’ into an asset, a massive energy resource. These materials which are already existing in the UK can deliver electricity for the whole of UK (Consumption UK 326.09 TWh per year in 2022. United Kingdom: Energy Country Profile - Our World in Data⁷) for about 7500 years. These numbers clearly show, no further mining is required for a substantial time. Also, it should be mentioned that this entire potential energy resource, capable of lasting for a very long time, is currently stored in only three buildings in the UK. This clearly demonstrates the energy density of the resource which will be made available through this new technology. Mining has been indicated as the main source of ecotoxicity [12] and CO₂ release, together with the enrichment process which is a very energy demanding process and is often one of the public concerns, see public concern 3. Countries with small spent nuclear fuel inventories and tailings, could find more attractive to use non-conventional Uranium resources [13].

3. CODE, MODEL AND METHODS

The description of the methods and models used in this work can be found in previous publications [14]. A summary of the full description provided in Ref. [15] is included here for general understanding of the obtained results. HELIOS 2.03 with the internal 173 group library [16] has been used for these simulations. “The general model is based on the EVOL benchmark configuration [17] which is transferred to a volume corrected 2D HELIOS model (see Fig. 3), that has been adopted to reproduce the 3D structure and the relations between different materials as closely as possible. The chosen buckling value has been fixed by a comparison of 2D HELIOS and 3D Monte-Carlo calculations within the EVOL benchmark exercises [18]. The leakage in radial direction is directly modelled through vacuum boundary conditions” [15].

The salt system chosen for iMAGINE is based on NaCl–UCl₃–UCl₄ with the eutectic formed at 42.5%–17.0%–40.5% [8].

⁵ <https://ourworldindata.org/energy/country/germany#how-much-electricity-does-the-country-consume-each-year>

⁶ <https://ourworldindata.org/energy/country/south-korea#how-much-electricity-does-the-country-consume-each-year>

⁷ <https://ourworldindata.org/energy/country/united-kingdom>

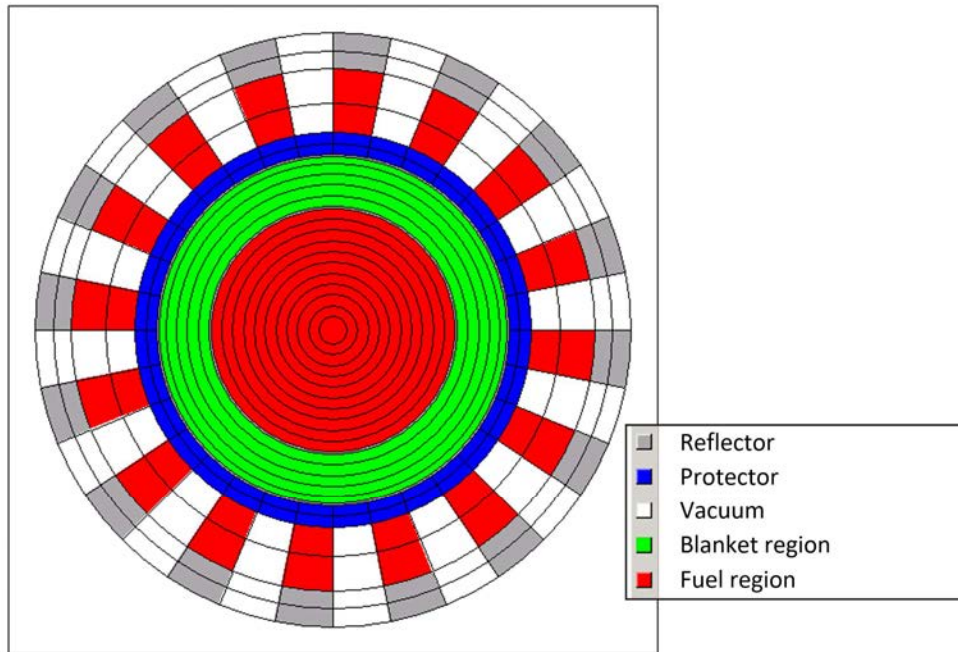


FIG. 3. Volume corrected 2D HELIOS model of the molten salt reactor (Reproduced from Ref. [15] with permission).

A PYTHON script has been developed [16] and the pre- and post-processor of the HELIOS system are used to create the input for the next cycle (see Fig. 4) and to simulate the salt clean-up. The system has already been validated against different codes. Theoretically, it would be possible to simulate a molten salt reactor precisely by using small time steps in this calculation loop.

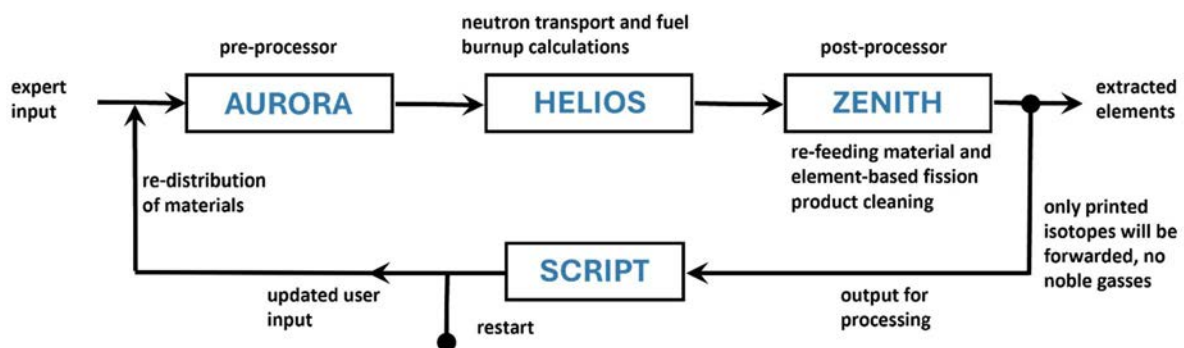


FIG. 4. Description of the calculation cycle for the simulation of an MSR, based on the HELIOS package (Reproduced from Ref. [15] with permission).

“The use of the described process has already been validated and used in several peer-reviewed publications (see Refs [16], [19], [20], [21]).

HELIOS is a light water reactor (LWR) code and a LWR spectrum is used for the weighting of the master libraries inside each energy group. Comparisons with other codes in the EVOL benchmark [18], in a fast reactor isotope accumulation test against SERPENT [5], as well as comparisons with SCALE/POLARIS [6][8] have shown good agreement. To verify the reliability of the results, a real reactor physics experiment for molten salt reactors would be required as discussed in Ref [6].

The approximations and the use of the HELIOS code package seem to be adequate. The results of the influence of different elements on the criticality of the system have been evaluated in earlier publications (see Refs [6]

and a detailed comparison to SCALE/Polaris is given in [14]. Recent studies have shown a significant difference between SCALE/Polaris and HELIOS in studies on the effect of Cl-37 enrichment [22]” [15].

This study will investigate the use of iMAGINE approach, see Fig. 5, for managing nuclear waste within P&T objectives. The evolution of transuranic elements Pu, Am, and Cm will be discussed for the reference case of long term operation and for other different scenarios.

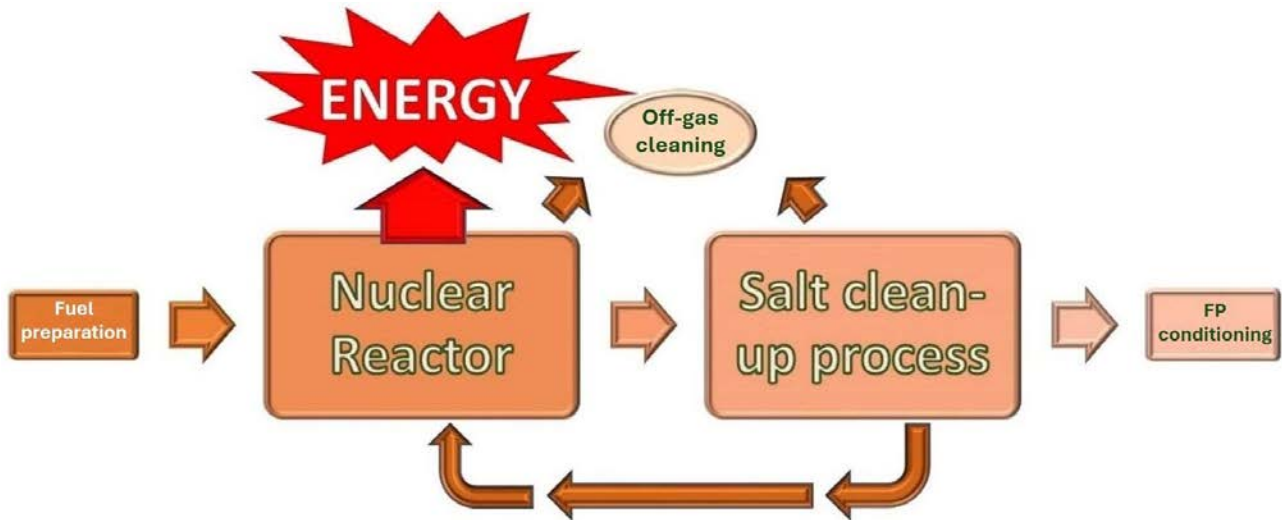


FIG. 5. Schematic of the iMAGINE approach based on a molten salt reactor with reverse reprocessing (Reproduced from Ref. [15] with permission).

4. DEMONSTRATION THROUGH MODELLING AND SIMULATION

The general demonstration of the long term operability of iMAGINE is based on modelling and simulation of the system over a longer time period and is given in Fig. 6. The operation is given for the staggered initiation of the cleanup system for different fission product elements indicated at the bottom of the figure. The aim of this staggered scheme is to balance the reactivity to extend the operational period through the cleanup initiation without relying on any active control measures, like control rods which would imply on the neutron economy. From modelling and simulation point of view, this approach assures the limitation of the error caused by the the keff normalization [12] on the results of breeding. The staggered cleanup approach allows studies on the long term behaviour to demonstrate the potential for self-sustained iso-breeding in the chosen molten salt reactor system with different feed streams, tailings as well as SNF. The long term investigation is essential to create a deeper understanding of the effect of feeding very small amounts of materials over a long time and get insights into criticality behaviour and material compositions.

The feed stream consisting of Uranium tailings can be seen as the reference case (see Fig. 6). This tailings feed case is accompanied in the figure by the SNF feed case for comparison. Tailings feed is the easiest operational mode in which U-238 already bred into Pu-239 is replaced after every 10 GWd/tHM burnup cycle by fresh tailings to ensure a constant amount of U-238 within a reasonable accuracy. This balances the amount of fertile material available for breeding. Salt cleanup for removing a certain additional element is activated every time the system criticality falls below 1. This is done by cleaning 20% of the target element(s) after the 10 GWd/tHM cycle. The order of initiating the cleanup of different elements follows the priority list as developed earlier [12]. This staggered approach allows reactor operation until ~900 GWd/tHM, related to the initial load, compared to ~200 GWd/tHM without cleanup.

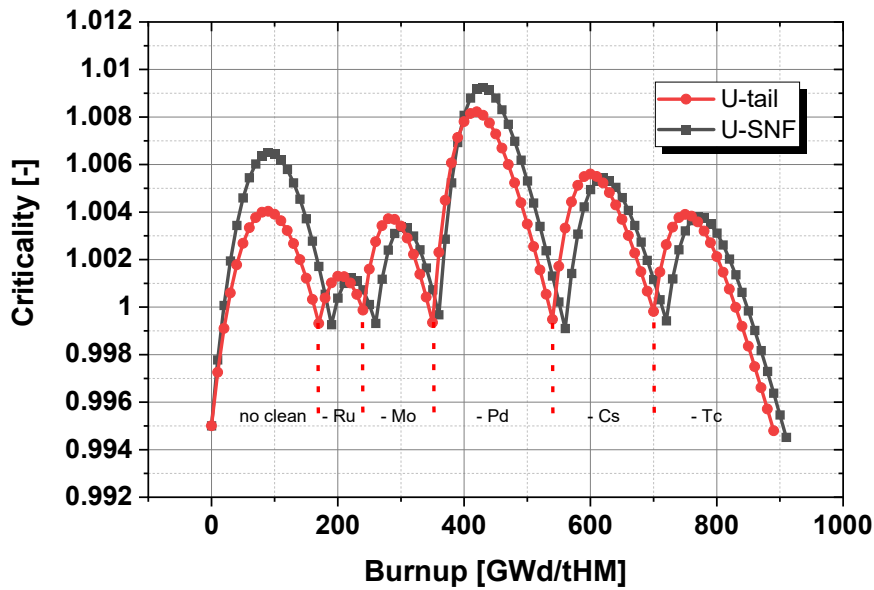


FIG. 6. Evolution of criticality over burnup for the Uranium started system with successive increase in the number of elements separated. Comparison of the tailings and the SNF feeding stream used to replace the U-238 which is consumed through breeding for the self-sustained long term operation.

The comparison between the tailings based case and the SNF feed case, indicates that the insertion of SNF provides a slightly higher criticality and finally, a slightly longer potential operation. This can be explained by two facts: a) the feeding of SNF adds a small amount of additional fissile material (Pu and remaining U-235 of the SNF) with every feed, b) the addition of fission products only has limited effect since a fast reactor system is typically less prone to neutron poisoning isotopes and can tolerate much higher fission product amounts than a thermal system. The change in fissile material content in the core and the transition from the initial core based on U-235 as fissile material to a Pu-driven core can be observed in Fig. 7. In the initial phase, the main Pu isotope bred is Pu-239. With increasing operational time, higher Pu isotopes are gradually formed in addition. The amount of Pu-239 becomes almost asymptotic after ~600 GWd/tHM while the buildup of higher Pu isotopes does not achieve an asymptotic value even at the end of the observation period. Comparing the two different feeding regimes, indicates a slightly higher total Pu content for the SNF fed system (pink line), compared to the tailings fed system (grey line) which is an effect of the pre-existing Pu content in the spent LWR fuels.

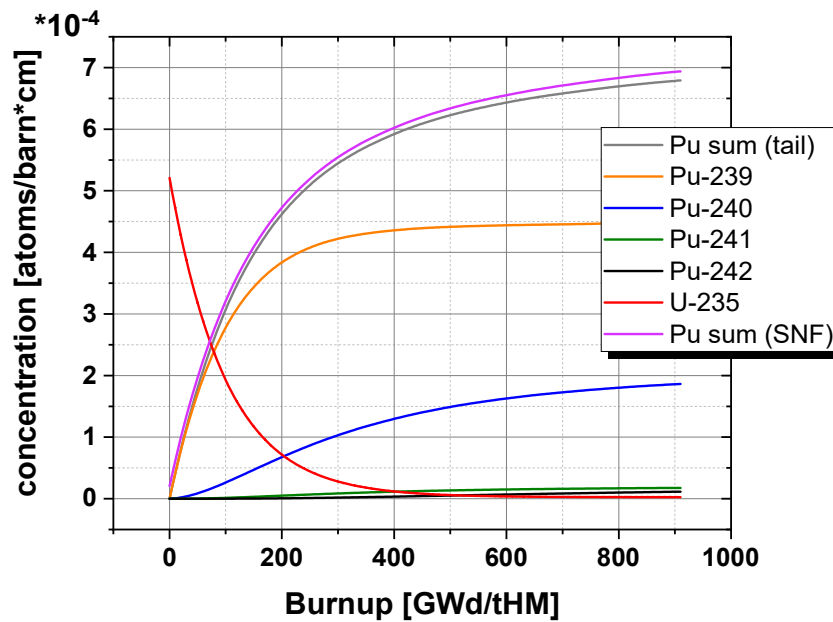


FIG. 7. Investigation of Pu production and vector as well as the fissile material balance over fuel burnup for the case with tailings feed and the SNF feed in the Uranium started system.

5. CONCLUSIONS

Nuclear has to play its role in delivering net zero energy for the future. This has been meanwhile recognized by several governments and has been supported through the IAEA. However, this will clearly lead to a substantial increase in the amount of SNF. Furthermore, if nuclear grows at the rate proposed during COP28, the supply of fissile material will become a problem on the longer term.

With iMAGINE, we have introduced a new, highly innovative system which is able to deliver the advantages of a closed fuel cycle system but with all steps integrated at one place. The system has been developed following the novel and revolutionary ternary visions; delivering unlimited nuclear energy, zero waste nuclear and accident free nuclear and integrating these technical aspects with the expectations of the public for a future nuclear system. These visions have been transformed into viable missions: to release a factor of 100 more energy out of the already mined nuclear material; to reduce the waste per energy to 1% or less compared to LWR open fuel cycle operation; to reduce the accident potential through reducing the driving forces and eliminating accidents initiators, as well as limiting proliferation risks. To successfully deliver iMAGINE, a stepwise project plan has been developed aiming at industrial demonstration in the 2040s.

The potential of iMAGINE regarding resource supply has been shown using the examples of Germany, the Republic of Korea, and the United Kingdom. For both Republic of Korea and Germany, the use of only already stored SNF could serve the total electricity demand of these countries for ~ 300 years at present consumption levels. Similarly, for the UK, the use of the SNF as well as tailings has been investigated demonstrating the potential of the iMAGINE technology to the full extent. Utilizing these ‘precious’ resource materials, which are already stored in the UK, could provide it with electricity for ~ 7500 years based on the current electricity production.

Finally, the operation of a self-sustained breeding system has been demonstrated through an advanced modelling and simulation approach using the lattice code HELIOS and a PYTHON script to model the long term operation without the need for fresh fissile material. The use of tailings and SNF as feeding material has been investigated and shows only minor differences in system operation with different feeding schemes. This fact indicates that unlike solid fuelled reactors, the iMAGINE system does not require a clean fuel supply, a

step which has the potential to make reprocessing as it is currently performed obsolete thereby eliminating the risk of proliferation and misuse of separated fissile materials, one of the biggest challenges of all closed fuel cycle systems. The application of reverse reprocessing allows in addition to create better separated waste streams which will allow to distinguish between elements containing isotopes with comparably short half-lives (30 year region) with high energy release and elements containing isotopes with very long half-lives, but low energy release. This approach has the potential to provide new, revolutionary opportunities in the final disposal strategy.

In general, different countries will have different priorities and views on what should be achieved through a future nuclear system, either the access to a very far-reaching energy resource, or a better solution for the nuclear waste management. Irrespective of the priority, iMAGINE will offer both opportunities simultaneously. However, it has to be kept in mind, what is proposed here is not a new reactor, it is a revolutionary whole nuclear energy system and will require a substantial development work. This is why the authors propose a substantial nuclear research, development, and demonstration (RD&D) programme with the aim to create a basis for future evidence-based decisions, e.g. in the case of Germany to answer the question Can the potential of iMAGINE to substantially reduce the final disposal challenge be proven?. The decision to postpone the site selection by at least 15 years has opened a precious time window - data for an evidence-based decision should be achieved now with a limited investment (< 5 % of the envisaged final disposal budget) into a RD&D programme. This will allow to use this time wisely to investigate a new approach into waste management to create certainty on a technology which has the potential to substantially change the demand and challenge of a future deep geological disposal.

ACKNOWLEDGEMENTS

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THE DEVELOPMENT OF SMALL MODULAR REACTOR SPENT FUEL AND RADIOACTIVE WASTE STRATEGIES FOR SASKATCHEWAN

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Extended Abstract

As part of the Canadian government's drive towards net zero carbon emissions the deployment of small modular reactors (SMRs) is being evaluated. Decarbonizing power production in the province of Saskatchewan will be especially impactful and challenging, given the current reliance on fossil fuels, existing large transmission and distribution network, and being a 'greenfield' jurisdiction without a nuclear power plant.

Building capacity and advancing knowledge surrounding nuclear power generation, and specifically SMRs, is particularly important for Saskatchewan as outlined by the provincial government in the Interprovincial SMR Strategic Plan. These benefits include the ability for SMRs to replace fossil fuels with baseload power, the deployment of micro-SMRs designed primarily to replace diesel use in remote communities and mines, and the ability of advanced SMR designs to produce high quality steam for heavy industrial applications and hydrogen production.

There are two proposals to deploy SMRs in Saskatchewan, one for the construction of BWRX-300s and an eVinci microreactor (sodium cooled high temperature reactor). To support the deployment these SMRs the Saskatchewan universities are working on strategies to minimize and manage radioactive waste produced by these types of reactors. Specific research activities include addressing the challenges surrounding the corrosion or corrosiveness of some SMRs spent fuel, with a focus on the incorporation of TRISO fuel into Canada's proposed deep geological repository (DGR) and the development of waste forms for molten chloride salts. The universities are also looking into safety improvements and providing support to the licensing of SMRs.

4. SUMMARY OF TECHNICAL SESSIONS⁸

4.1. TRACK 2 – STORAGE OF SPENT NUCLEAR FUEL AND VITRIFIED HIGH LEVEL WASTE AND SUBSEQUENT TRANSPORTABILITY

Track Leaders' Overview: Koji Shirai (Japan/CRIEPI) and Tom Boyce (USA/NRC).

The track comprised four sessions covering spent fuel characterization, cladding behaviour, country overviews and new design applications.

The renewed interest in spent fuel characterization is related to spent fuel dry cask loading and in support of spent fuel disposal. It is important to know the characteristics and properties of the spent fuel because uncertainties impact the design and the cost of storage or disposal facilities. Progress in spent fuel characterization technical basis has focused on technical gaps. This has highlighted the need for experimental investigations through direct measurement of irradiated materials, as well as the integration by novel techniques such as machine learning aimed at reducing uncertainties.

Confirmation/generating data in support of ongoing spent fuel integrity in storage is important for providing confidence to key stakeholders that the fuel is safely stored and can be readily retrieved and transported. Various studies related to spent fuel integrity of several cladding types in wet and dry storage conditions were shared. The objectives of these studies were to ensure the safety of all relevant operations during storage, prior to disposal or reprocessing or to further understand potential degradation mechanisms. In this respect, studies into understanding the behaviour of hydrogen which goes into solution during the drying of zirconium clad fuels and the form in which it subsequently precipitates during cooling/the impact on clad mechanical properties which have attracted much interest over the last decade continue.

Overall, there is increased confidence that national or multinational spent fuel and high level waste repository will be feasibly developed. Availability for most countries, however, is still some decades away which is impacting existing nuclear programmes in terms of the need for additional storage or renewal of cask/storage facility operating licences. The trend towards the use of dry storage to replace wet storage facilities or to provide additional spent fuel storage capacity continues.

New design applications have focused on dual purpose cask/transport cask applications/evaluations to meet current and future industry needs. Existing systems have been evaluated for the storage and transport of spent fuel from small modular reactors and microreactors.

Summary:

- Several countries presented their work on characterizing the radionuclides in spent fuel, particularly for thermal and criticality analyses.
- Uncertainties often lead to excess conservatism in the design of the safety features. At the same time, reducing conservatism requires specialized and costly research infrastructures.
- Two countries conducted inspection of fuel rods in wet storage that showed little change in cladding properties between fuel in 25 (stainless steel) and 50 years (zirconium), giving confidence to continued wet storage.
- Specific fuel clad degradation studies on the stress corrosion cracking of stainless steel clad fuel and hydride reorientation in zirconium clad materials have been undertaken.

⁸ Track 1 on National Strategies for Spent Fuel Management was covered as panel discussions. The summaries, presented papers and extended abstracts can be found in the dedicated section "SUMMARY OF PANELS" as Panels I and II.

- Phenomenon identification and ranking tables (PIRT), based on the latest findings from the USA high burnup cask demonstration programme, have been used in a review of the peak fuel drying temperature limit in the US NRC Regulatory Guide 3.54. With additional research, the information can potentially be used to raise the current limit. Countries are making plans for extended storage time periods beyond the initial planned period of operation and are conducting research to support renewals and inspections.
- Some countries reported that they are constructing new storage facilities to accommodate additional spent fuel.
- Several specific examples of new developments were presented affecting individual countries or organizations.
- An early general assessment is that transportation and storage of spent fuel from advanced reactors is feasible using modifications to existing systems. However, there may be operational challenges that would need to be considered, such as needing to reduce the volume of spent fuel transported or stored.

Session 2.1 – Spent Fuel Characterization

Session Chairs: Manuel Martin Ramos (EC/JRC) and Bogalech Kejela (Ethiopia/Ethiopian Radiation Protection Authority, YG Challenge Winner)

Session 2.1 comprised of five papers, three from Switzerland, one from Finland and one from the United States of America, dealing mainly with the characterization of spent fuel.

- **Paper ID76 by A. Shama, (Switzerland)** presented the characterization of the Swiss spent nuclear fuel inventory for the planning of the Deep Geological Repository. Switzerland's four nuclear power plants (NPP) spent fuel is classified as waste at the end of life (EOL) and is intended to be disposed of at a deep geological repository (DGR), planned for 2050/2060. NAGRA, the Swiss waste management agency, uses two databases one with the current inventory, and the Model Inventory of Radioactive Materials (MIRAM), which additionally adds future waste arisings, on the basis of 60 years operation of the Swiss NPP, and that is used for safety assessments, planning and implementation of the DGR. To this end, a methodology for the characterization of spent nuclear fuel has been developed. The methodology allows the characterization of three parts of the spent fuel (i.e. the fuel, the cladding, and the structural material), based on computer codes calculations at fuel assembly level taking as input the characteristics of the irradiation and cooldown cycles. Mr Shama explained in detail the different steps of the methodology, the input data and codes used for each element (SCALE, ORIGEN, MCNP, with the nuclear data library ENDF), the effect of impurities, the use of actual measurements and actual data for verification and validation, and the outcome (i.e. radionuclide inventory per part, and the decay heat). Accurate decay heat characterization is required for efficient operation and optimal spent fuel assembly distribution. The methodology, which is automatized, also accounts for the impact of impurities and allows for optimization and uncertainty analysis. To questions from the floor, Mr Shama clarified that chemical interactions were dealt with under a different programme and provided some additional details on the impact of uncertainties in the DGR planning and implementation.
- **Paper ID59 by S. Häkkinen, (Finland)** presented VTT Finland's work on computational spent fuel characterization to better understand the variables influencing Serpent 2 calculations and identify essential parameters important for handling and disposal of spent fuel. After describing the context of VTT activities in the area of spent nuclear fuel and a summary of the most important factors that influence its long term management, Ms Häkkinen provided more detailed results, analysing for example the impact of burnup and assembly type (BWR, VVER, EPR) in the calculation of decay heat, including the identification of the main contributors (in terms of radioisotopes), the impact of enrichment on the concentration of mobile radioisotopes, the impact of the choice of modelling parameters, and the impact of the void fraction in the decay heat and the multiplication factor. Ms Häkkinen described the Kraken computational framework to compute nuclide inventory in 3D complete core geometry, as well as Serpent validation on criticality safety and decay heat. The presentation finalized with gaps and challenges of computational spent fuel characterization and recommendations for future work on the topic. To a question from the chair, Ms Häkkinen acknowledged the challenges in the determination of the impact of the void fraction due to the uncertainties of the void fraction and nuclear data.
- **Paper ID127 by E. Vlassopoulos, (Switzerland)** presented a report of a recently completed Euratom research project on Spent Fuel Characterization and Evolution Until Disposal. The European joint research programme EURAD gathers 20 EU Member States and 3 Associated Countries, 51 mandated organizations, and 61 linked third parties, and comprises 13 Work Packages: 10 on RD&D, 2 on strategic studies, and one on knowledge management. The work package object of the presentation aimed at better understanding the behaviour of spent nuclear fuel during prolonged storage and subsequent handling and disposal in a deep geological disposal facility, during normal, abnormal and accident conditions. Modelling work has to be supported and complemented with experimental results. The presentation focused mainly in codes validation, in particular decay heat codes by means of a blind test using calorimeter data (which yielded that BWR spent fuel decay heat calculation show higher uncertainties than PWR spent fuel, and that the uncertainties are dominated

by the calculation-experiment (C-E) variance), and materials mechanical performance codes and finite element analysis, by means of mechanical testing of cladding and fuel rods, both during the evolution until disposal, and under abnormal and accidental conditions (methodology to be developed also under the same project). Mr Vlassopoulos finished his presentation listing recommendations for future work, including among others more experiments. To the questions of the floor, the presenter provided additional information and clarifications regarding the applicability of cladding only (without fuel) tests and the impact of hydrogen in the structural integrity of the fuel rod.

- **Paper ID132 by H. Akkurt, (United States of America)** presented an overview of decay heat measurements at the Swedish spent fuel storage facility (CLAB) carried out between 2003 and 2021 under the EPRI–SKB collaboration.

Decay heat is a key parameter for the management of spent fuel, as it establishes operational limits for both storage and disposal. Decay heat measures (published and unpublished) present in some cases high uncertainty or quality issues. However, as they are the only measurements available for some spent fuel characteristics for short or long cooling times, they cannot be screened out until new accurate, good quality measurements are available. EPRI and SKB partnered to evaluate and publish previously undisclosed decay heat measurements from spent nuclear fuel, validate the measurements using a variety of code and cross-section libraries, and perform additional measurements to close technical gaps using a calorimeter with updated calibration curves. The new validation set will broaden the validation range and offer accurate readings with low uncertainty and provide decay heat measurements for short and long cooling periods. The new validation set will support a more flexible and efficient management of the spent fuel in all stages of storage, transport and disposal.

A publicly available EPRI study will include an evaluation and release of CLAB decay heat measurements taken between 2003 and 2021. To questions from the floor, Ms Akkurt clarified the typical duration of the measuring periods and their restrictions, as well as the challenges of measuring decay heat in the short time after irradiation.

- **Paper ID144 by S. Caruso, (Switzerland)** presented a new calorimeter concept for the measurement of the decay heat of spent fuel assemblies in the Gösgen Nuclear Power Plant.

At the Swiss Gösgen Nuclear Power Plant, researchers are proposing a new concept for a full size spent fuel calorimeter to detect the decay heat of PWR fuel with high enrichment, very high burnup, and mixed oxide fuel to be installed in the spent fuel pool. The calorimeter, which consists of a vessel in the pool of the spent fuel wet storage facility, is designed to achieve high measurement precision. Mr Caruso provided details of the design; and technical characteristics of the calorimeter, touching upon the mechanical design, thermal–hydraulic design. cooling variants and safety features, as well as some insights on the dynamic behaviour of the calorimeter and the precision (1 %). The measurements of this setup will complement decay heat data available elsewhere (e.g. CLAB) and will allow to measure decay heat from high burnup UOX and MOX spent fuel. The licensing application is currently under preparation.

To the questions of the public, Mr Caruso clarified that the only possible place to install such a calorimeter is in the spent fuel pool, and only after a careful and thorough safety assessment and a licence from the regulatory authority.

Session 2.2 – Cladding Behaviour

Session Chairs: Efstathios Vlassopoulos (Switzerland/NAGRA) and Marissa Bell (USA/DOE, YG Challenge Winner)

Session 2.2 comprised of six papers, two from the United Kingdom, one from Canada, one from the Republic of Korea, one from Germany and one from the United States of America.

- **Paper ID36 by R. Veazey, (United Kingdom)** presented the management of Advanced Gas cooled Reactors (AGR) fuels based on the operational experience of Sellafield Ltd. In particular, the technical basis for extended wet storage of AGR fuel was explored. Due to changing context and subsequent strategy shift from reprocessing to longer storage times, higher storage density, and potential for fuel failure, the management strategy has to be adapted to accommodate those challenges prior to the

expected spent fuel disposal (~2075). Effects of such long term wet storage were evaluated, including implementing long term dosing solution, the effectiveness of pH with increasing levels of chlorine, upgrading cooling capabilities, and testing of a new container design and isolation capabilities. Conclusions noted that based on operational experience, there is continued confidence in the existing wet storage regimes for longer term use.

- **Paper ID156 by G. Cota-Sanchez, (Canada)** presented the history, background and recent updates related to R&D studies on the effects of long term wet storage on Canadian Spent Nuclear Fuel. This presentation gave an overview of three experimental campaigns on sister rods examinations at different storage time periods. The experimental campaigns focused on a series of Post Irradiation Examinations (PIE) on spent fuel and cladding. The first experimental campaign, examining 16 years of storage, found no significant deteriorating effects. The second experiment examined 26 years of storage, while no significant effects on the cladding were observed, a sediment-like deposit and UO₂ oxidation hydrates were found. The third campaign examined from 2018 onward, finding again no significant effects due to the prolonged storage conditions. Overall, the conclusions noted negligible non-significant effects of long term storage, which provide the technical basis for the proof of safety during wet interim storage.
- **Paper ID17 by D.-H. Kook, (Korea, Republic of)** presented results from Ring Compression Test (RCT) experiments on unirradiated Zircaloy-4 pre-hydrogenated cladding tubes. The tests followed a thermomechanical loading of the cladding samples along with a slow cooling rate. Tests were performed in selected time periods between 1 day and 24 months of cooling. Results indicated that slow cooling rate showed more hydride reorientation in the radial direction and therefore less ductile behaviour. A few temperature interruptions during the slow cooling of the samples were evaluated to have no significant impact based on the testing assumptions. In principle, RCTs on samples with hydrogen concentrations of less than 500 ppm revealed ductile behaviour, independent of their slow cooling time history. In contrast, some samples with higher concentrations showed offset strain of less than 2%, indicating more brittle behaviour. Conclusions noted the brittle tendency of slow cooling effects, with higher hydrogen concentrations also contributing to such brittleness. The failed samples were also investigated with metallographies to get further insight into their failure modes.
- **Paper ID57 by C. Gallagher, (United Kingdom)** presented the contexts and priorities for assessing drying and dry storage options for AGR spent fuel. With storage (wet) designed for reprocessing and shifts from reprocessing to interim storage pending a deep geological repository in 2075, fundamental research is needed to assess demonstration of safety of drying mechanisms and interim dry storage of stainless steel clad spent nuclear fuel. Previous studies have found spent AGR fuel to be more vulnerable to stress corrosion cracking (SCC) in cave atmospheres c.f. wet storage. The main topics of research focused on four areas related to wet storage, transition from wet to dry storage, dry storage conditions and disposability. Preliminary results indicated the need for further modelling and experimental work in areas such as progression of SCC and other deterioration mechanisms, as well as on methods for drying AGR fuel, and developing suitable dry storage environments.
- **Paper ID90 by U. Zencker, (Germany)** presented the behaviour of long term dry storage on the brittle failure limits of spent fuel claddings. Hydrogen absorption could lead to the formation of hydrides in the claddings, preferably in circumferential direction, however, when claddings are subjected to high temperatures and mechanical loads, hydrogen can dissolve and re-precipitate as hydrides in radial directions during slow cooling. Ring compression tests observed failures due to crack propagation along radial hydrides. Results provide insights into important characteristics such as stress strain relations. In addition, fractographies were conducted to investigate the failure mechanisms. The experimental studies were complemented by numerical investigations using finite element modelling. The fracture was simulated with a cohesive zone model. The model was calibrated against many experimental results (both from surrogate and irradiated samples), and it can reproduce the major load drops observed due to the propagation of cracks along radial hydrides. A plastic stress strain relation describing the material behaviour primarily in the hoop direction was determined. Conclusions noted potential applications to different cladding materials.
- **Paper ID134 by J. Faldowski, (United States of America)** presented the re-examination of spent fuel cladding integrity limits based on high burnup demonstration cask project. Actual storage temperatures have been found to be consistently lower than expected. Subsequently, additional

research was conducted on Phenomenon Identification and Ranking Tables (PIRTs), focusing on five different phenomena. Results indicated there is no abrupt onset of fuel failure. Also, the Regulatory Guide 3.54 significantly overestimates decay heat over a wide range of burnups. The conservatism in thermal calculations leads to negative impact on worker dose and fuel performance. Moreover, effort was given on redefining gross rupture, where the reactor coolant system chemistry records from operation may be used to determine accordingly the storage requirements. Finally, increasing peak cladding temperature (PCT) to 450°C is potentially acceptable during the drying process prior to the dry interim storage. Leveraging results from all PIRTs the safety can be improved by reducing the number of fuel moves (i.e. risk), decreasing dose to workers, and increasing regulatory efficiency. It was noted that additional research is required to establish the technical basis for those conclusions.

Session 2.3 – Country overview

Session Chairs: Tom Boyce (USA/NRC) and Uwe Zencker (Germany/BAM)

Session 2.3 comprised of five papers, one from Germany, one from Ukraine, one from Ghana, one from the United States of America and one from Slovakia.

- **Paper ID72 by J. Palmes, (Germany)** presented the German concept for the management of high level radioactive waste (HLW) and spent nuclear fuel (SNF). After dry storage in dual purpose casks, a direct disposal in a deep geological repository is planned. Whilst the German Site Selection Act assumes the decision for the repository site to be taken in 2031, a decision is expected until at least 2046 according to the current schedule. License renewal for the dual purpose casks and interim storage facilities is needed. The licensed storage period for each storage facility presently covers 40 years. Additionally, the approved storage period for each cask is limited to 40 years from closure of the primary lid after loading of the cask. The first cask was closed in 1992 and will reach its 40 years limit in 2032. The 40 years are not a physical or technical, but a political limit for durability. Incidences that would be able to significantly affect safety of the storage facility or of a single cask did not occur. The package design approvals for each cask type are undergoing repetitive renewal procedures according to the state of the art of science and technology. Research on degradation mechanisms is necessary for extended storage. A strategy for communication and dialogue with stakeholders is being developed to support public acceptance. During the discussion, it was asked whether it is planned to open the casks for further insights, which was denied. According to a comment from the audience (BGZ/Maik Stuke), no scientific progress is expected and, foreseeable, no site will be available for that because of the dismantling of nuclear facilities in Germany.
- **Paper ID87 by A. Shepichak, (Ukraine)** presented experiences, challenges, and breakthroughs in regulatory oversight of the construction, commissioning, and operation of spent fuel storage facilities in the Ukraine. All issues were successfully resolved by implementing changes that were reviewed and approved by the State Nuclear Regulatory Inspectorate of Ukraine. Currently, spent fuel in Ukraine is stored in the spent fuel wet storage facility (ISF-1), the spent fuel dry storage facility at the ZNPP site, the spent fuel dry storage facility (ISF-2), and the spent fuel central storage facility. The dry storage facility for spent fuel (ISF-2) was put into operation in 2021. Construction of the central storage facility for spent fuel has been completed and the facility is currently in the commissioning phase. In the discussion, it was explained that centralized storage facilities were favoured particularly in light of the Russian occupation. Currently there are no plans for a repository.
- **Paper ID108 by M. Asamoah, (Ghana)** presented Ghana's path in the field of nuclear technology, which began in 1961. Despite setbacks, Ghana remained committed to nuclear development, culminating in the establishment of the Ghana Atomic Energy Commission (GAEC) and subsequent initiatives in nuclear research and education. With the passage of key legislation, particularly the Nuclear Regulatory Authority (NRA) Act 895 of 2015, a solid legal framework for nuclear activities has been established that emphasizes safety, environmental protection, and international cooperation. The ongoing development of a national policy for the management of radioactive waste and spent fuel underlines Ghana's commitment to the responsible use of nuclear energy. In the discussion, it was explained that there is a workforce of 90 people in the NRA. Concerning the reaction of the people in

the country for the nuclear strategy, a public acceptance of 78 % in favour was mentioned. There are efforts to gain public acceptance for a repository, but it is also seen as a multinational task.

- **Paper ID65 by M.Z. Bell, (United States of America)** presented on innovation and ensuring meaningful stakeholder participation in decision making. The consent based site selection process focuses on equity, transparency, and the various facets of environmental justice. The presentation focused on procedural, recognition and intergenerational justice and provided deeper insight into how the US DOE engages the public in the process. At each stage of the process, US DOE is integrating procedural justice mechanisms and will work closely with communities to define and refine what it means to consent, what it means to engage in consent based siting, and what it means to construct a consolidated interim storage facility. By prioritizing the needs of communities and people, US DOE can both effectively implement environmental justice and develop a solution for spent fuel management in the United States of America. In the discussion, it was noted that the question of whether to have a repository and where to locate it is a common problem. A site has not yet been selected. The public acceptance of consolidated interim storage facilities and repositories is an important issue, a consent based siting is a good base.
- **Paper ID138 by J. Václav, (Slovakia)** presented on experiences with SNF management. The first SNF was taken to the Soviet Union, respectively the Russian Federation, but since the end of the 1980s all SNF has been stored in a Slovak interim storage facility for spent fuel for the long term. As the capacity of the wet storage facility is insufficient, Slovakia decided to build a new storage facility for SNF in accordance with legal regulations. The new dry storage module will enable safe long term storage of SNF and will accommodate the production of all six VVER-440 units during their 60 years of operation. In the future, the stored SNF will be deposited in a DGR after construction of a repository, with reprocessing being another option.

Session 2.4 – New Design Application

Session Chairs: Koji Shirai (Japan/CRIEPI) and Anna Detkina (UK/University of Liverpool, YG Challenge Winner)

Session 2.4 comprised of five papers, one from the Russian Federation, one from Lithuania, one from the United States of America and two from Spain.

- **Paper ID6 by M.E. Budu, (Russian Federation)** presented the paper ‘New dual-purpose casks for spent fuel of foreign WWER NPPs and high level waste from spent fuel reprocessing’. She outlined the concept design of dual-purpose casks for SNF and HLW from spent fuel reprocessing, the development of the regulatory framework and the milestones achieved and planned activities in cask management. Key features of the 137T series casks, including their capacity, structural design and test results, were highlighted to demonstrate progress in SNF and HLW management and storage solutions.
- **Paper ID33 by A. Šmaižys, (Lithuania)** presented the paper ‘Modifications of the interim spent fuel dry storage facility for the storage of fresh fuel’. He presented the main technical issues related to the development of the storage of transport casks with fresh fuel assemblies and packaging canisters with fuel pellets, resulting from the decommissioning of the Ignalina power plants, together with dry storage CONSTOR RBMK1500/M2 casks in a single hall in the SNF interim dry storage facility. He also provided insights into the criticality safety analysis of normal and accident conditions, such as moderator intrusion into the transport cask. It was demonstrated that the storage facility could safely accommodate both fresh and spent fuel under normal and accident conditions.
- **Paper ID109 by P. Narayanan, (United States of America)** presented ‘Performance enhancement of the NUHOMS EOS dry storage system and the TN EAGLE transportation cask for used fuel management’. He outlined the design concept of the Extended Optimized Storage (EOS) system and the TN EAGLE cask to be used for the management of spent nuclear fuel, including that from Advanced Reactor Fuel Types (e.g. fast reactors, TRISO, metallic and Molten Salt Reactors (MSR) fuel). He also provided insights into the design, operational performance and improvements of their proposed system, and highlighted the technical challenges for the introduction of MSR SNF into the existing storage system.

- **Paper ID77 by F. Lentijo, (Spain)** presented ‘Complementary facility for cask recovery at ISFSI’. He outlined the design concepts for a complementary cask recovery facility with a hot cell to be compatible with the National Framework Policy for Radioactive Waste and Spent Fuel Management. The design of the facility includes several modes of operation, including the ability to inspect, maintain, repair, and refurbish casks, mitigate unlikely cask failures, assess whether a cask meets regulatory transport requirements, and make necessary modifications. He also highlighted the project's milestones and schedule for commissioning the facility.
- **Paper ID52 by R. Marín, (Spain)** presented ‘Spent nuclear fuel management for HOLTEC International’s SMR-300’. He discussed Holtec's spent fuel management solutions for the SMR-300 reactor, including the high capacity multipurpose canisters (MPCs) designed for long term confinement, transportation, spent fuel storage and eventual disposal. He also highlighted the integration of the Spent Fuel Pool (SFP) into the containment structure of the SMR-300. It provides capacity for at least four operating cycles and includes an area for loading and/or unloading of spent fuel casks.

4.2. TRACK 3 – TRANSPORTATION IN THE BACK END OF THE FUEL CYCLE

Track Leaders' Overview: Pierre Malesys (France/Independent), Steven Maheras (USA/PNNL), George Burnett (UK/NTS), and Yukio Okabe (WNTI).

The track comprised two sessions covering national experiences, and current and future challenges.

Anticipation is the key word. Planning for transport has to start early.

Summary:

- Some of the fuels from small modular reactors (SMR), advanced modular reactors (AMR) and all other types of next generation represent significant shipping challenges that have to be adequately addressed and not underestimated. Transport needs to be considered when developing these new types of reactors. A reactor is worth nothing if its fuel cannot be shipped!
- International transport of floating nuclear power plants (FNPPs), transportable nuclear power plants (TNPPs) and microreactors is an emerging area and may (will?) require changes to the transport regulatory framework for these reactors to be commercially viable.
- For existing nuclear power plants, 'early' can mean three years or more prior to shipping, especially when transport package design licensing is involved. Actions to be anticipated may include:
 - Stakeholders and public engagement, including tests adapted to the audience;
 - Development of an appropriate regulatory infrastructure, including emergency preparedness and response, for newcomers and/or for emerging needs (transportable nuclear power plants, etc.);
 - Design, testing, licensing, manufacturing and commissioning of new casks, for current fuel designs with higher enrichment and higher burnup, also for future fuel (new fuel designs, small modular reactors, advanced modular reactors);
 - For new campaigns of shipments from existing power plants, detailed review of the infrastructure, including on-site visits;
 - Ageing management for extended period of storage;
 - Training of the involved teams (e.g. casks operators, emergency responders, etc.).

Session 3.1 – National experiences

Session Chairs: Yves Solignac (France/ Orano) and Christy Alistan (France/ Orano NPS)

Session 3.1 comprised of four papers, one from France, one from Poland, one from the Russian Federation and one from Switzerland.

- **Paper ID114 by Y. Solignac (France)** presented an overview of Orano NPS technical assistance team and some of the latest developments to ensure safe and efficient transport operations. To check static and dynamic transport package clearances within customers' facilities, a scanner is being used to produce 3D images of the transport route which are coupled with CAD models of transport packages. Another service being offered is the checking/adjustment of the hydrogen content of dried casks to meet safety case/regulatory limits. The technical assistance team is being sustain through the training and investment in students in their own university.
- **Paper ID20 by V.N. Ershov (Russian Federation)** presented an overview of transportation in the Russian Federation. The various transport packages used in the Russian Federation for national and international transports were outlined. Details were also provided on the state processes for the design, certification of transport and storage casks, the organization of transport and emergency response. Looking forward dual purpose casks are being evaluated for the long term storage of fuel and highly active waste. Further consideration has been given to the transport of small modular reactor spent fuel and the transport of microreactors. It was suggested that revisions to existing international regulations would be required for the latter.
- **Paper ID110 by F. Hotzgrewe (Switzerland)** presented an overview of spent fuel management (SFM) in Switzerland in the context of Mühleberg NPP shutdown in 2019. Since 2002, Switzerland has adopted an open cycle policy where spent fuel is either wet stored at reactor or dry stored pending the availability of a repository in 2060. Mühleberg NPP fuel route is limited in terms of the cask size. The reactor operates two TN9/4 transport casks which can accommodate seven BWR fuel assemblies. SFM involves road transporting the fuel to the central dry storage facility Zwilag where the fuel is transferred in a hot cell to large storage casks. Originally TN25BH casks were used with a capacity for 69 fuel assemblies (FAs). Due to decay heat requirements this was reduced to 65 FAs and for the last core loading the Castor V/52 was used.
- **Paper ID32 by L. Bak (Poland)** presented the lessons learned from the return of Polish research reactor fuel to the country of origin. As part of the global threat reduction initiative, spent fuel from research reactors Maria and EWA were returned to the Russian Federation between 2009 and 2016. There were eight transports using either TUK-19 or the Skoda VPVR casks. All but one transport was by road, rail and sea. The last shipment was by road and air. The steps involved in making the returns happen and the differences between the transport by road/rail/ship versus air were outlined.

Session 3.2 – Current and future challenges

Session Chairs: Steven Maheras (USA/ PNNL) and Lukasz BAK (Poland/ NCBJ, YG Challenge Winner)

Session 3.2 comprised of four papers, four from the United States of America and one from France.

- **Paper ID42 by H.E. Adkins (United States of America)** presented the development and regulatory approval process for transportation of microreactors, specifically referring to transportable nuclear power plants (TNPPs). Microreactors are designed to be factory built and modular, making them suitable for transport by truck. However, the transportation of TNPPs containing irradiated fuel poses significant regulatory challenges, as the US Nuclear Regulatory Commission (NRC) has never licensed such a process. The irradiated fuel in TNPPs would require an NRC approved Type B package but meeting the NRC's requirements under Part 71 of Title 10 of the US Code of Federal Regulations for such packaging is unlikely. A risk informed approach to address these challenges, involving the demonstration of a proposed risk assessment method was applied to a TNPP prototype under project Pele. Future demonstrations may include transporting irradiated TNPPs on public roads, thus requiring

regulatory approval from both the NRC and the US Department of Transportation (DOT). The findings and insights from this implementation were summarized. The ultimate goal is to ensure the safe transport of TNPPs containing irradiated fuel, addressing the unique challenges posed by their modular and transportable nature.

- **Paper ID41 by S.J. Maheras (United States of America)** presented transportation of microreactors containing irradiated fuel and the associated emergency planning challenges. Microreactors are designed for transportability by truck, rail, vessel, or air. Their deployment is driven by the need for power in remote locations, military installations, and disaster recovery sites. However, transporting these reactors, particularly with irradiated fuel, presents unique challenges due to their design and the potential unfamiliarity of state emergency responders. Key challenges include the need to revise the US Department of Transportation Emergency Response Guidebook to include specific guidance for microreactors, the implementation of a risk informed process for transportation package approval, and the need to conduct external engagement with States and Tribes prior to transport. Emergency response planning has to address various aspects such as emergency response organization, support, and resources. Specific challenges also arise from the use of hazardous materials in microreactor designs, such as beryllium and sodium. Beryllium is being considered as a replacement for graphite as a neutron moderator, while sodium is being present in heat pipes. Both materials pose additional risks that have to be accounted for in emergency response planning, particularly regarding the interaction of sodium with water and the modification of firefighting guidelines. Additionally, transportation accident recovery plans may need to be developed as part of the US Nuclear Regulatory Commission (NRC) transportation package approval process. The concept of operations for microreactor transport varies by mode. For highway transport, microreactors containing irradiated fuel would be shipped from deployment sites to factories or depots after cooling to reduce radiation dose rates. These shipments would require overweight/over dimension permits and compliance with hazardous material safety regulations. Rail transport involves similar procedures, with microreactors shipped on railcars meeting specific standards and potentially escorted by buffer railcars and rail escort vehicles. For vessel transport, microreactors would be shipped on Class INF-3 vessels or barges, depending on the proximity to shore.
- **Paper ID148 by C. Alistan (France)** presented the transportation and interim storage solutions for spent fuel from Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs). The critical challenges and necessary strategies for managing the spent fuel from these next generation reactors were outlined. The primary challenges identified include ensuring safety, mitigating proliferation risks, addressing logistics early in the reactor design process, and developing competitive solutions through innovation and collaboration. It is proposed to utilize proven technologies combined with cutting edge innovations to create modular and flexible cask systems. Specifically, Orano NPS has developed several cask solutions for triple purpose cask for transport, storage, and disposal. It was also suggested that existing licensed casks for initial SMR/AMR development phases could be reused. The large fleet of versatile casks can be adapted with minimal modifications to meet the unique requirements of SMR/AMR spent fuel management. The need for adaptable, modular, and economically competitive cask solutions to support the safe and efficient transportation and interim storage of SMR/AMR spent fuel was emphasized. The importance of early logistics integration in reactor design and the potential benefits of reusing existing cask technologies were two areas where the emerging needs of the SMR/AMR industry could be met. While current solutions are robust, ongoing innovation and adaptation will be necessary to address future challenges in spent fuel management for advanced nuclear reactors.
- **Paper ID67 by S.J. Maheras (United States of America) on behalf of L. Hay** presented the development of a functions and requirements document for a spent nuclear fuel (SNF) transportation package performance demonstration (PPD). It is intended to involve public participation and potentially employ full scale physical testing of an SNF transportation rail cask. The need for stakeholder engagement to ensure public trust and confidence in the safety of SNF transportation was highlighted. Stakeholder input is vital, and the US Department of Energy (DOE) plans to involve diverse entities such as federal and state agencies, industry, and interest groups. This approach aims to ensure meaningful participation and confidence in the PPD process. One of the primary considerations for the PPD is the selection of an appropriate SNF transportation cask. The chosen cask needs to be a

high capacity cask with a significant mass, on the order of 136 to 191 t. The cask could be transported by rail, heavy haul truck, and barge. The importance of using analytical tools for pre-test and post-test analyses was brought up. The development of the PPD functions and requirements document representing a comprehensive approach to addressing the challenges of SNF transportation. By incorporating stakeholder engagement, selecting appropriate transportation casks, and employing rigorous analytical tools and full scale testing, the safety of transport would be demonstrated.

- **Paper ID141 by Y. Liu, (United States of America)** presented the topic of packaging safety, security, and safeguards (3S) for nuclear fuel cycle materials in storage, transportation, and disposal. The critical role of packaging in the safe, secure, and safeguarded management of nuclear fuel cycle materials during transportation, storage, and disposal was discussed. Packaging systems have to be designed to maintain the containment of radioactive materials, provide radiation protection, and ensure criticality control across all stages of the nuclear fuel cycle, which includes conversion, enrichment, fuel fabrication, power generation, storage, reprocessing, and disposal. The concept of safety, security, and safeguards (3S) by design is essential for the effective lifecycle management of nuclear packaging. The importance of ageing management, which addresses the prevention, mitigation, condition monitoring, and performance monitoring of ageing effects on the packaging systems were highlighted. Effective ageing management is vital to maintaining the integrity of packaging over time, and remote monitoring technologies, such as ARG-US, play a crucial role in this process. The PDCA (Plan/Do/Check/Act) cycle was emphasized as a framework for continuous improvement in ageing management programmes. In conclusion, the effective management of packaging is essential for the sustainable future of nuclear energy. Continuous advancements in technology and the transfer of knowledge are crucial to address the evolving challenges in the management of nuclear fuel cycle materials.

4.3. TRACK 4 – RECYCLING OF SPENT FUEL

Track Leaders' Overview: Darshit Mehta (India/BARC), and Rod McCullum (USA/NEI).

Papers were presented in two oral sessions, one focused on near term opportunities (involving Japan, Republic of Korea, Russian Federation and France) and the other looking further ahead (involving Russian Federation, France and Belgium).

Japan and Republic of Korea focused on opportunities to develop fast reactor reprocessing. Japan explored the behaviour of actinides and fission products in irradiated advanced reactor fuel while Republic of Korea concentrated on opportunities to reduce the volume of waste generated. Both discussed experimental and development work that could be applied to improve isotope recovery processes. In a related paper, Belgium presented the interim results of their Advanced Separation for Optimum Management of Spent Fuel (ASOF) isotope recovery process which focused on the fabrication of transmutation targets instead of fast reactors.

In the Near Term Opportunities session, France presented details on the performance of fuel assembly concepts that have been developed to utilize Plutonium from recycling PWR MOX. These concepts were shown to be capable of stabilizing both plutonium stockpiles and spent fuel inventories without affecting overall reactor operations. In the Future Forward session, France explained how this and other work was being factored into a long term strategy for modernization of France's reprocessing infrastructure in the 2040 to 2060 timeframe.

Russian Federation described work on High Temperature Gas Cooled Reactor (HTGR) spent fuel reprocessing. The work is so far inconclusive, but future work with irradiated fuel is planned.

Russian Federation also presented a detailed examination of accident tolerant nuclear fuel reprocessing technology development. Experimental testing results were described, and a flowsheet of the process was presented.

Finally, Russian Federation provided new details of how fuel lease/takeback could be supported by recycling through a waste substitution exchange – returning a higher amount of short lived heat generating isotopes to customer countries while retaining longer lived byproducts for disposal in the Russian repository. This would convey the mutual advantages of leaving the customer country with only low and intermediate level wastes to dispose of while reducing the heat load in the Russian high level waste repository.

Nine posters were presented. The posters focused on spent fuel waste treatment approaches (Canada, Russian Federation, and Republic of Korea), advanced reactor enabling technologies (Egypt, Russian Federation, and United States of America), and enhancements to existing technologies (Libya and Russian Federation).

Session 4.1 – Near term opportunities

Session Chairs: David Hambley (UK/NNL) and Hugo Vincenti (France/Orano, YG Challenge Winner)

Session 4.1 comprised of four papers, one from Japan, one from the Republic of Korea, one from France and one from the Russian Federation.

- **Paper ID106 by M. Nakahara (Japan)** presented an outline of the development of fast reactor fuel reprocessing in Japan through a series of programmes that studied the behaviour of actinides and fission products using irradiated fast reactor fuel from a number of different fast reactors, including some from overseas countries. Solvent extraction experiments have evolved from recovery of U and Pu to include Np and co-extraction for these materials and their demonstration using recycled spent fuel.
- **Paper ID43 by C.-B. Lee (Korea, Republic of)** presented a description of studies on the use of sodium cooled fast reactors (SFRs) for reducing the volume of waste generated from current and anticipated future power reactors. Recovered uranium, Pu and long lived minor actinides, such as Np, Am, and Cm, are to be fabricated into metallic SFR fuel. A prototype 150MW(e) SFR demonstration plant has been designed at a level that enables safety assessment of the reactor. Safety, safeguards and economics of operating this conceptual fuel cycle to recycle PWR spent fuel were assessed and used to identify key areas for development work to improve the efficiency and durability of pyroelectrochemical processes and enhance the TRU burning capability of the prototype SFR.
- **Paper ID112 by G. Vaast (France)** presented details of two fuel assembly concepts that have been developed to use Pu derived from recycling of PWR MOX in EPRs. The safety and operational performance of full and partial core loads were assessed, concluding that a partial (30%) core loading of MOX2 fuel with natural uranium enriched assemblies was able to efficiently use recycled plutonium, although the ¹⁰B enrichment rate of the shutdown rod control cluster assemblies would need to be at least 50%. This approach has the potential to stabilize both plutonium stockpiles and spent fuel inventories with a fleet of PWRs. The study also showed that an increase in plutonium content or the ²³⁵U enrichment of the UO₂ fuel assemblies would enable recycling with lower plutonium fissile quality without affecting overall reactor operations.
- **Paper ID7 by E.D. Filimonova (Russian Federation)** presented work on head end processes for prismatic HTGR SNF reprocessing. This included design and experimental work on recovery of compacts from an assembly, including pressing out and drilling compacts, TRISO particle recovery from compacts by electrochemical disintegration and kernels recovery from pyrocarbon by voloxidation. Laboratory testing using unirradiated HTGR fuel and surrogates has demonstrated the feasibility of the main head end operations. Several waste streams were identified, some of which will require novel waste forms to be developed. The volume of these wastes is large, and deployment would require new active facilities. It was not clear whether reprocessing would be beneficial for the proposed HTGR installation. Further work with irradiated fuel is planned.

Session 4.2 – Future forward

Session Chairs: Darshit Mehta (India/BARC) and Elizaveta Filimonova (Russian Federation/SC VNIINM, YG Challenge Winner)

Session 4.2 comprised of four papers, two from the Russian Federation, one from France and one from Belgium.

- **Paper ID9 by L.N. Podrezova (Russian Federation)** presented spent accident tolerant nuclear fuel reprocessing technology development and experimental testing results. The perspective fuel composition is triuranium disilicide (U₃Si₂). High silicon content in the fuel determines necessity of special processes development. Two main technological approaches are taken: adaptation of existing hydrometallurgical technology and pyrochemical reprocessing in molten molybdenum salts. Adaptation approach requires studies of cladding behaviour during washing in nitric acid solutions,

voloxidation of the fuel, dissolution and clarification of the voloxidated fuel. Intermediate results of the voloxidation testing on non-irradiated fuel showed complete oxidation of U_3Si_2 to U_3O_8 after 4 hours at 600°C. Voloxidated fuel (uranium part) was completely dissolved in 8–9 mole/l nitric acid solution at 95°C over six hours, while non-voloxidated pellets resulted in a SiO_2 coating that prevented further reaction. Around 0.5% of U remained on the cladding after the washing, with irreversible losses of U less than 0.01%. A self-regulating filter with a package made of metal spherical powder was used for clarification testing. Clarification factor from silicon of more than 1000 was achieved. Studies of the non-voloxidated fuel dissolution in molten $MoO_3+Na_2MoO_4$ mixture showed complete dissolution, which means that voloxidation step is not necessary for pyrochemical technology. A principal flowsheet of accident tolerant nuclear fuel reprocessing in molten molybdenum salts is presented.

- **Paper ID61 by H. Vincenti (France)** presented the French strategy towards cycle closure starting in the near future. The strategy is based on short, mid, and long term needs of the country. The main focus is reducing natural uranium consumption while increasing MOX fuel production for future fast neutron reactors. MOX and ERU recycling are a step to complete closure of the French nuclear cycle. This requires La Hague (reprocessing) and Melox (fuel fabrication) existing facilities to be modernized. Prolonging the lifetime of existing facilities to 2040 and a maximum of 2060 will allow for long term continuity of the countries fuel cycle while it develops new technologies to adapt to future challenges. New facilities are also considered with the flexibility to recycle spent fuel with different approaches such as recycling MOX with mono as well as multirecycling and the multirecycling of UOX. Currently these new fuel cycles are being evaluated for the deployment in the existing French nuclear fleet replacements as a stepping stone to multirecycling in liquid metal cooled fast reactors (LMFRs).
- **Paper ID131 by K. Lemmens (Belgium)** presented the interim results of the Belgium's ASOF project (Advanced separation for the optimal management of spent fuel). Its main goals are R&D of new and innovative processes for the separation, conversion, and conditioning of spent fuel within the Belgium framework. Transmutation of minor actinides is also in ASOF project scope as a part of the MYRRHA, a demonstration transmutation facility. The ASOF project is divided into four work packages. They include separation of higher actinides and short lived fission products from irradiated nuclear fuel, conversion of the americium concentrates to oxide for the production of transmutation targets, waste conditioning for separated waste and the impact of separated wastes on the final geological repository. A flow sheet for the co-management of platinum group metals and americium is presented. The feasibility of the advanced separation of minor actinides and Cs + Sr fraction by TODGA and TEDGA has been proved using centrifugal contactors on simulated tracer spiked highly active PUREX raffinate. The hybrid internal gelation and infiltration route was chosen for americium transmutation target fabrication. $Am_yU_{(1-y)}O_2$ product with 5–30 mol. % of Am (y) was obtained. Geopolymers are considered a possible conditioning matrix for partitioned waste streams. The radiological impact has been studied.
- **Paper ID3 by T.A. Aleksandrova (Russian Federation)** presented Sustainable Nuclear Fuel Cycle (SNFC) strategy of Russian Federation for countries with Russian designed nuclear power plants. The strategy is based on waste substitution, i.e. the equivalent activity principle. It includes reprocessing of customer's SNF and returning only a part of the reprocessing wastes. Reprocessing technology for WWER SNF with the separation of short lived isotopes, mainly caesium and strontium, has been developed. The disposal of this fraction is possible at intermediate depth instead of DGR in the case of normal HLW from reprocessing activities. From the Russian side, this strategy has positive impact on costs for the construction and operation of the DGR located in the Nizhnepanskiy gneiss crystalline rock mass, Russian Federation. The possibility of SNFC strategy implementation is fully covered, from SNF reprocessing to cask management, disposal, and safety analysis. A concept design and a safety analysis report for a standard radioactive waste disposal facility for short-lived caesium-strontium fraction from the fuel complying with Russian and international standards has been developed. A summary of the results is presented.

4.4. TRACK 5 – DISPOSAL OF SNF, HLW AND OTHER WASTE FORMS IN DEEP GEOLOGICAL REPOSITORIES (DGR)

Track Leaders' Overview: Leon Kegel (Slovenia/ARAO), David Hambley (UK/NNL), and Anders Sjöland (Sweden/SKB).

The disposal track comprised two sessions on disposal strategies and implementation, and on technical and scientific aspects of disposal.

Insights into the ongoing efforts of various countries to develop and implement safe and effective deep geological repository solutions for radioactive waste disposal were presented by various countries. The importance of securing fuel information, cost estimation transparency, and adapting disposal strategies to accommodate existing or new waste forms was highlighted. Technical advancement and development of novel/optimized canister designs that could potentially accommodate various waste forms and be used for different disposal concepts have been presented. To underpin this development, reliable and accurate data on spent nuclear fuel and host rock properties need to be available.

It is evident that some countries have made significant progress in SNF disposal projects, but slow or delayed siting process remain one of the important impediments for final disposal. Diverse SNF inventory, including future SMR/AMR, its characterization and information keeping is another disposal challenge, but countries are developing solutions to this, for example by developing uniform disposal canisters systems or using machine learning tools.

Disposal cost optimization is important. Regular cost estimation revisions need to be prepared and based on clear national policy and strategic decisions that have significant cost impact such as open vs. closed fuel cycle, disposal in mined DGRs or in deep boreholes, constructing one or more DGRs for existing and future SMR fuels, and others.

Session 5.1 – Disposal strategies and implementation

Session Chairs: Leon KEGEL (Slovenia/ARAO) and Virginie Solans (Sweden/Uppsala University, YG Challenge Winner)

Session 5.1 comprised of six papers, one from France, one from the United Kingdom, one from Sweden, one from Switzerland, one from Finland and one from Argentina.

- **Paper ID120 by M. Maertens (France)** presented the readiness of the French DGR (Cigéo) project. The geological repository (Cigéo) concept for Intermediate Level – Long Lived waste and HLW was introduced. Since 2020, the project entered the licensing process. In July 2022, Cigéo was recognized as a national public utility project after consideration of the supporting file that included environmental and socioeconomic evaluation. The construction licence application was submitted in January 2023. The process for obtaining the licence was presented, including current steps and major milestones. The disposal concept is mature, and some examples of full scale demonstrators were shown, such as the construction of full size galleries in the site specific underground research laboratory. A full scale funicular to transfer waste between the surface and the underground repository has also been built and tested on the surface. Finally, package retrieval tests from corroded HLW cells were illustrated.
- **Paper ID80 by J.J. Dunsford (United Kingdom)** presented the recent progress with respect to geological disposal of high heat generating wastes (HHGW) in the UK. An overview of the R&D programme for the deep geological disposal of HHGW including spent nuclear fuel (SNF) and materials associated with the reprocessing of SNF was presented. Geological disposal is planned for a range of materials arising from historic UK nuclear fuel cycle operations as well as arisings from ongoing reactor operations. Nuclear Waste Services (NWS) is working on a consent based siting process with three community partnerships to evaluate the suitability of sites within these communities to host a future geological disposal facility (GDF). The process is founded on the two key principles of a willing community and a suitable site. The key aims of the HHGW R&D programme and mechanisms employed to deliver these aims were outlined. The experimental methodologies in assessing waste form dissolution behaviour were described with reference to HLW glass and AGR fuel. The future direction of the R&D programme will be aligned with the ongoing GDF siting programme and the availability of site specific data, from deep borehole investigations. In addition, complementary R&D activities associated with underpinning the deep geological disposal of thermally treated intermediate level waste will be undertaken. Active engagement with international partners and sister waste management organizations to foster knowledge exchange and the application of international best practice will also continue.
- **Paper ID124 by F. Johansson (Sweden)** presented the challenges associated with collecting and preserving sufficient SNF information before the fuel is placed in the final repository. Nuclear power plants being in operation before plans for final disposal or even the creation of SKB have created some issues. As the requirements for the final disposal were not known then, and to reduce disk space, some information from the past, such as core follow-up data or cladding material, was lost or incomplete. Moreover, the challenges of having two databases for different purposes (transportation and interim storage) were also highlighted during the presentation. SKB conducted a project between 2018 and 2020 to identify and fill gaps in these databases. Lessons learned include ensuring legal rights to fuel information and saving fuel information in a data format that can be used in the future. It was emphasized that fuel information is an important asset for the waste management organizations, and necessary to optimize the back end system, and there will never be a better occasion than now to start securing that you have necessary fuel information.
- **Paper ID111 by D. Mignone (Switzerland)** presented a framework for estimating the costs of disposing of radioactive waste in Switzerland. The requirements of the Swiss legal framework for establishing a funding mechanism to secure the disposal of radioactive waste in deep geological repositories was presented, including worked examples and references. To avoid cost overruns, it was stated that regular reviews, revisions and verification are required. Complemented by introducing and monitoring success factors for cost estimations such as consistency, completeness, and transparency.

The basis of cost breakdown structures was given, emphasizing that the data needs to be plausible, sound, properly allocated and structured, and include long and short term planning, contingencies and risks. This was supported by worked examples and an overview of the tools used by NAGRA to develop and support cost assessments. After submitting the general licence application for a DGR end of 2024, NAGRA will renew and optimize its cost estimations and look to further develop and optimize the costs.

- **Paper ID71 by P. Keto (Finland)** presented an adaptation of the current final disposal strategy and methods in Finland for spent fuel from SMRs. The possible adaptation of Finland's final repository solution for nuclear waste to accommodate SNFs from SMRs was discussed. Several legal challenges, noting that disposing of SNFs from SMRs is not straightforward and would require new licensing and potentially the establishment of a new disposal site, were outlined. Moreover, there are specific challenges associated with the disposal of SNFs from SMRs, particularly their interaction with groundwater and potential issues arising from mixing with existing waste in the currently designed repository. It was also pointed out that the radionuclide inventory of SNFs from SMRs differs from that of LWRs, impacting safety factors such as criticality and decay heat.
- **Paper ID63 by L. Kniznik (Argentina)** presented SNF management and the new ConfinAR Geo project for the disposal of high and intermediate level waste. In Argentina, SNF is regarded as a potential energy resource due to its fissile material content. The decision to adopt an open or closed cycle policy will be made in the future. The currently SNF management practices were outlined, and an introduction to the new ConfinAR Geo project given. The goal of the ConfinAR Geo Project is to implement a deep geological disposal system for existing spent fuel and other wastes, as well as wastes generated from the commissioning of the CAREM small modular reactor prototype, and the RA-10 multipurpose reactor and decommissioning wastes. In the absence of a decision on reprocessing, the R&D programme and safety case have to be developed considering two possible options which are spent fuel reprocessing or direct disposal.
Deep geological repository will be required regardless of the fuel cycle option finally adopted. However, recycling has the potential to benefit repository development by converting spent fuel into waste forms that are easier to dispose.

Session 5.2 – Technical/scientific aspects of disposal

Session Chairs: Bengt Hedberg (Sweden/SSM) and Diana Manrique (Mexico/UNAM, YG Challenge Winner)

Session 5.2 comprised of six papers, two from the United Kingdom, one from the Republic of Korea, one from Sweden, one from the United States of America and one from Türkiye.

- **Paper ID85 by M.J. Austin (United Kingdom)** presented the NDA's strategy for managing the UK's SNF, focusing on the challenges of metallic uranium fuel. He noted that metallic fuels are not compatible with the disposal concepts developed by NWS and highlighted issues of corrosion, hydrogen generation, and heat output. To mitigate the risks, approaches like dry storage in self-shielded cast iron containers (SSBs) have been developed and are being evaluated for geological disposal without additional reprocessing. He also discussed ongoing efforts to find an optimized approach for managing these fuels.
- **Paper ID16 by K.-L. Lee (Korea, Republic of)** presented KAERI's development activities to improve the current Korean spent fuel disposal reference system (KRS+). The reference system is based on the KBS-3 method developed by Sweden, and KAERI is investigating measures to improve the system for use in Republic of Korea. Research focuses on the development of high performance waste containers with improved corrosion resistance and advanced shock absorption materials. In addition, alternative concepts such as deep drilling and a multilevel version of KRS+ are being analysed and evaluated. The implementation of KRS+ is expected to reduce the area required for waste disposal and improve long term safety.
- **Paper ID40 by K.J. Robinson (United Kingdom)** presented an alternative approach for the management of certain spent fuels compared to the UK SNF strategy. The current strategy envisages storing all spent fuels at Sellafield until disposal, typically as high heat generating waste, in a future

geological disposal facility. The alternative approach involves conditioning of the fuels in question for potential future disposal as low heat generating waste in the geological disposal facility.

- **Paper ID38 by V. Solans (Sweden)** presented the outcome from a study exploring whether the accuracy of decay heat predictions can be enhanced by incorporating measurement data. The purpose is to improve decay heat prediction for spent fuel assemblies, optimizing their combination in copper canisters for disposal in a geological disposal facility. The presentation highlighted the use of a machine learning model combining traditional fuel parameters with gamma and neutron data. Results showed that integrating calculated and experimental data significantly improves prediction accuracy, essential for the safe and efficient management of spent nuclear fuel.
- **Paper ID78 by J. Sloane (United States of America)** presented an ongoing project to develop Waste Acceptance Criteria (WAC) for advanced reactor waste forms in the Universal Canister System (UCS). This system is designed for use in both mine disposal facilities and borehole disposal. The goal is to provide a disposal option for numerous advanced reactor waste streams before the construction and commissioning of advanced fuel cycle facilities and reactor designs. The project involves designing the canister, characterizing advanced reactor waste forms, and developing generic WAC. Significant progress has been made in canister design and regulatory review. This project aims to ensure an integrated and cost effective waste management system for advanced nuclear waste.
- **Paper ID11 by B. Bulut Acar (Türkiye)** presented a study on the effects of variations in the thermal properties of host rock on a potential disposal facility for spent nuclear fuel and vitrified HLW. The study emphasizes the importance of accurately characterizing the thermal properties of the host rock during site investigations to select an appropriate site for a spent fuel disposal facility. Findings indicate that thermal conductivity and specific heat significantly impact the required disposal area, influencing the design and capacity of geological repositories.

4.5. TRACK 6 – IMPACTS OF ADVANCED NUCLEAR ENERGY SYSTEMS ON THE BACK END OF THE FUEL CYCLE

Track Leaders' Overview: Hong Jang (Korea, Republic of/KAERI), Laura McManniman (USA/EPRI) and George Xu (Canada/CNL).

This track focused on the potential impact of the introduction of advanced nuclear reactors on current fuel cycle back end arrangements and explored the associated possible complexities and opportunities, and comprised two sessions.

Five papers and associated presentations largely centred on advanced reactor technologies and their impact on back end fuel cycle strategies. Two papers and associated presentations from Canada predicted the spent fuel characteristics from three small modular reactors including a thermal spectrum molten fluoride salt reactor (MSR), a high temperature gas cooled reactor (HTGR), and a sodium cooled fast reactor (SFR). The characteristics found to be most impactful on the back end fuel cycles were the chemical forms of the spent fuels, while management of the radiological characteristics were found to be likely comparable to the spent fuel arisings from current light and heavy water cooled reactors. A paper from France presented potential integrated management solutions including interim storage systems, transportation, and used fuel recycling technologies envisaged by advanced reactor vendors or users. These included both existing solutions and perspectives for the future, e.g. the implementation of 'symbiotic fleets' of LWRs and advanced fast reactors to reduce the high level waste (HLW). A paper from the USA summarized the current state of advanced reactor development and the resulting considerations for developing back end solutions. This paper introduced a joint project Waste Integration for Small and Advanced Reactor Designs (WISARD) organized by OECD Nuclear Energy Agency (NEA) that is looking to coordinate these research and development efforts. The impact of SMR deployment on multinational cooperation within the back end fuel cycle, including the introduction of a Multinational Repository (MNR), was analysed in a UK paper that explored the links between potential SMR deployment and current nuclear energy programmes.

More country specific data was presented in three papers on the roles of MSRs in the back end fuel cycle of the future energy system in Europe. A paper presented by Belgium on the European Project MIMOSA (Multirecycling strategies of LWR SNF focusing on MOLten SAlT technology) developed and analysed tangible strategies for multirecycling of LWR SNFs in EU countries within MSRs. Similarly, the French paper presented detailed activities of the Innovative System for Actinides Conversion (ISAC) project and the approaches to achieve the activity objectives - the feasibility of actinide conversion in MSRs and the impact of MSRs deployment on waste inventories. More data was presented on Pu reduction and burning in MSRs and a new modelling tool of MSR fuel depletion calculation in the third paper from France.

Three papers explored the impact of new reactor technologies on current national fuel cycle programmes and strategies. A UK paper discussed potential HTGR spent TRISO fuel management strategies in the UK, concluding that spent TRISO fuel is suitable for storage and direct disposal utilizing current technologies, and that reprocessing is not seen as a viable option. A Ukrainian paper presented the challenges of SMR development and deployment in Ukraine, including the current lack of the back end fuel cycle management strategies and facilities, and negative public perceptions on nuclear energy from the Chornobyl accident. Research activities for regulatory readiness for various advanced non-light water reactor (ANLWR) fuel types such as metal fuel, TRISO pebbles, and molten salt fuel and the back end fuel cycle were summarized in a US NRC paper. An IAEA paper presented the role of 'safeguards by design' in supporting the development of sustainable spent fuel management strategies for advanced reactors and the benefits that can be gained through early engagement with the IAEA Department of Safeguards during reactor and back end technology development.

Session 6.1 – R&D for advanced reactors relevant to the back end fuel cycle

Session Chairs: George Xu (Canada/CNL) and Nehad Abdelwahab (Egypt/ENRRA, YG Challenge Winner)

Session 6.1 comprised of six papers, one from Canada, two from France, one from Belgium, one from the United States of America and one from Ukraine.

- **Paper ID26 by X. Wang (Canada)** presented computational models for two small modular thermal neutron spectrum reactors (Fluoride Molten Salt Reactor (SM-FMSR) and High Temperature Gas cooled Reactor (SM-HTGR)) to calculate the fuel depletion within the lifetime of the reactor. The calculated spent nuclear fuel (SNF) characteristics and chemical and physical forms were then compared to those of CANDU spent fuel, currently the only power generation reactors in Canada, to highlight the impact on SNF storage, transport, and reprocessing. Some interesting results included: the SMRs spent fuel have a lower inventory of short lived radionuclides; SM-FMSR spent fuel has the highest neutron emission; SM-HTGR spent fuel has the highest gamma emission after a few years of decay but is similar to CANDU spent fuel in the longer term.
- **Paper ID88 by P.-E. Dufour (France)** presented a tool (PYMS code) to estimate isotopic evolution for actinides transmutation dedicated to fast molten salt reactors. The use of fast molten reactors is to reduce the long lived high level waste (LL-HLW) inventory. The tool was demonstrated with the conceptual ARAMIS-A reactor, a fast MSR designed for transmutation of minor actinides, employing a quaternary salt fuel system ($NaCl-MgCl_2-PuCl_3-AmCl_3$). A point of note is that 99 wt.% ^{37}Cl will need to be used to reduce the production of ^{36}Cl . Two reference codes MOSARELA REM were also used in the calculations for comparison. The reported differences were small.
- **Paper ID51 by A. van Heek (Belgium)** presented MIMOSA (Multirecycling strategies of LWR SNF focusing on Molten Salt technology) Project that develops and analyses tangible strategies for multirecycling of LWR SNFs in EU countries within MSRs. The project addresses and evaluates the long term nuclear energy needs in the EU. In doing so, SNF/Pu/RepU management, infrastructure availability and infrastructure deployment scenarios are considered on four levels, future nuclear energy demand, nuclear systems, MSR functions and nuclear fuel cycle options. In terms of MSRs, key aspects of the technical feasibility and performance of chloride MSRs will be demonstrated simultaneously by calculations/ simulations and experimental investigations.
- **Paper ID37 by M.-S. Chenaud, (France)** presented the detailed activities of the Innovative System for Actinides Conversion (ISAC) project and the approaches to achieve the activity objectives in France. Project scope includes studying the feasibility of an MSR for actinides conversion, assessing the impact of the deploying MSRs on waste inventories, and federate the French nuclear sector around these technical objectives.
The project overarching objective is to establish if this technology is advantageous in reducing waste burdens.
- **Paper ID142 by T. Boyce, (United States of America)** presented the US NRC research activities on ANLWR fuel types to aid licensing activities. The US NRC's regulatory planner for identifying gaps that require research and US NRC's approach to gather information was discussed, including Phenomena Identification and Ranking Table (PIRT), Active Coordination, NRC Research, and Proactive Approach. Reports have been published from the research activities and are available to be viewed. The list of current issues that the US NRC is looking to resolve includes understanding unique technical challenges and requirements for storage and transportation of advanced SNF, assessing the performance of spent TRISO and metallic fuel under storage conditions and the applicability of safety codes and standards, and assessing continued storage options for MSR salt waste.
- **Paper ID21 by B.P. Zlobenko, (Ukraine)** presented the SMR development and implementation information in Ukraine in the backdrop of significant negative impact from the Chornobyl and Fukushima incidents on the public acceptance on nuclear energy. Four water reactor type SMRs were discussed. However, the New Energy Strategy to 2035 lacks information on the future of the back end of SNF management in Ukraine. The so called deferred decision between SNF reprocessing and direct disposal was accepted for long term SNF storage, as a consequence of there being no national

infrastructure for the reprocessing or disposal of SNF. These conditions were foreseen to introduce significant challenges on the long term storage of SNFs from SMRs, as it is unknown what new facilities will be needed.

Session 6.2 – Analysis of the impact of advanced reactors on the back end of the fuel cycle

Session Chairs: Rod McCullum (USA/NEI) and Paul-Edouard Dufour (France/EDF, YG Challenge Winner)

Session 6.2 comprised of six papers, one from France, one from the United States of America, two from the United Kingdom, one from the IAEA and one from Canada.

- **Paper ID64 by C. Evans (France) on behalf of I. Morlaes**, presented a review of advanced nuclear reactors in terms of the opportunities and challenges for the back end of the fuel cycle. The results from an in-depth screening of advanced reactors technologies by fuel type (oxide/ceramic, TRISO, metallic alloy, and liquid fuels) and how they impact manufacturing, transportation, processing of nuclear fuel and disposal considerations was provided. Reactors of the future will raise questions on all these topics as they will either use existing technologies and extend their current use or rely on completely new concepts. Back end concepts were described as falling into one of three categories: spent fuel management, valorization of recovered material, and waste conditioning and disposal optimization. It was observed that the best option for TRISO fuels is direct disposal. In contrast to the specific case of chloride fast spectrum molten salt reactor (FS-MSR), there are potential synergies between the chemistry of its reprocessing and the existing La Hague reprocessing set-up.
- **Paper ID94 by L. McManniman (United States of America)** presented Electric Power Research Institute's (EPRI's) perspective and involvement in the WISARD project. Currently there are 83 advanced reactor designs across 18 countries. The need to balance diluted versus targeted funding, many and distinct versus few and related projects, and the interests of fast followers versus first movers were highlighted. Waste Integration of Small and Advanced Reactors Designs (WISARD) is a joint project carried out by the NEA with participation of EPRI. At EPRI, the necessity to assess the impact of advanced reactor concepts on the back end of fuel cycle is being recognized as crucial and leads to substantial global collaborations to advance in that direction.
- **Paper ID95 by J. Kinghorn-Mills (United Kingdom)** presented a comparative study on the potential impacts of different SMR technology deployment on multinational cooperation at the back end of the fuel cycle. This work introduced five main SMR categories and chose a reactor type that is considered representative of those categories identified. The study proceeded with the analysis of those different reactor types in the light of upstream and disposal relevant parameters in the case of a 'once through' strategy. Finally, the paper identified five categories of countries based on their links with nuclear energy and examined trends for deployment of SMR in those categories of countries. Different strategies for deploying deep geological repository were discussed as was the impact and synergies between deployment of multiple types of SMR.
- **Paper ID119 by J.J. Whitlock (IAEA)** presented the role that 'safeguards by design' can play in supporting sustainable spent fuel management strategies. Safeguards implemented by the IAEA are regarded as critical to ensure peaceful use of nuclear energy. 'Safeguards by design' is the practice of taking into account safeguards requirements during the design process to avoid retro fitting. As nuclear energy needs to scale up both in total installed power and re-usability to meet climate change mitigation targets, implementing modernized techniques for safeguards will be a crucial aspect of this expansion in avoiding unnecessary dose to inspectors and better utilization of their time. Four activities in the nuclear fuel cycle where implementing 'safeguards by design' has played an important role include: dry storage, advanced reactors, reprocessing and geological disposal. Disposal safeguards were of particular interest during the Q&A following the presentation with the presenter concluding that such safeguards would need to be in place as long as there is an IAEA.
- **Paper ID93 by L.E. Kissick (United Kingdom)** presented a spent fuel management strategy for High Temperature Gas cooled Reactor (HTGR) fuel, UK context. A review of HTGR fuel cycle options at the scale of potential deployment in the United Kingdoms was outlined. Both prismatic and pebble arrangements of TRISO fuel particles in the core are options being studied. Fuel storage, reprocessing,

recycling and separation possibilities for HTGR fuel were described and the possible synergies or differences with existing PWR and AGR facilities were highlighted. The integration of HTGR fuel in the current fuel cycle in the UK concerning transportation and disposal was analysed. It was concluded that reprocessing and recycling of HTGR fuel was not viable. However, it was noted that these fuels have significant advantages in storage, transportation, and disposal. These included protective capabilities of the fuel form in storage and transportation, the possibility that these fuels could be ready for disposal in as short as five years, and the opportunity for the fuel to be disposed of in 'bespoke casks' as the long term survivability of graphite could be credited so that repository designers would not need to rely as much on the function of the cask.

- **Paper ID123 by D.T. Wojtaszek (Canada)** presented an assessment of the performance and spent fuel characteristics of a generic 100 MW(e) class small modular sodium fast reactor (SFR-SMR). The spent fuel characteristics for a 286 MW(th) pool type Sodium Fast Reactor (SFR) with metallic high assay low enriched uranium (HALEU) fuel have been studied. The core would have a lifetime of 30.5 years and could reach a burnup of 140.2 MWd/kg before recharge becomes necessary. It was established that criticality could be guaranteed from the beginning to the end of core life over this timeframe. Some preliminary conclusions were drawn from the analysis regarding the content of spent fuel in terms of reusability of the plutonium in SFR or thermal reactors. It was observed that the spent fuel would have a high plutonium content which would make it attractive for reprocessing/recycling but could also be seen as a concern from a non-proliferation standpoint.

4.6. TRACK 7 – ACHIEVING INTEGRATED SPENT FUEL MANAGEMENT

Track Leaders' Overview: Cecile Evans (France/Orano), Bengt Hedberg (Sweden/SSM) and Efstathios Vlassopoulos (Switzerland/Nagra).

This track discussed various aspects of an integrated spent fuel management system with views from embarking countries illustrated by Nigeria, countries having yet to make decisions on the implementation of their spent fuel management programmes like Mexico and Argentina, as well as countries having made progress in implementing their programmes.

Some papers emphasized the role of simulation/scenarios analysis of the system as well as involvement of various stakeholders when assessing spent fuel management options and identifying key drivers and decision milestones, as presented by Belgium. These aspects are crucial in supporting the development of a comprehensive analysis of the various management scenarios, whether to serve as bases for assessments of potential options or for technical and financial optimization projects. For the latter, the presentation from Switzerland emphasized the importance of using accurate data and carefully considering associated uncertainties.

The presentation from France underlined the importance of developing a complete and comprehensive long term vision on the nuclear fuel cycle involving all relevant stakeholders i.e. industries, technical support organizations (TSOs) and safety authorities. The importance of political support in this context is identified as a key success factor. The significance of an integrated approach was also emphasized in the presentations from TEPCO on recent progress made on the complex task of removal of spent fuel and retrieval of fuel debris at the Fukushima Daiichi NPP.

The development of a complete fuel cycle system, including the management of spent fuel takes several decades. Key features in such processes include leveraging from significant experience, dedicated research and development, including sharing of existing infrastructures, as well as using assessment and optimization tools, and enabling cross generation knowledge and expertise transfer with the aim to achieve continued public support for the implementation of optimized system solutions.

Session 7.1 – Achieving integrated spent fuel management

Session Chairs: Cécile Evans (France/ Orano) and Laura Kniznik (Argentina/ CNEA)

Session 7.1 comprised of four papers, one from France, two from Japan and one from Nigeria.

This session encompasses embarking and large nuclear countries with Nigeria, France, Japan, coming from different background academics, Technical and scientific support organizations (TSOs) and nuclear operators. It is to be noted that this session was unique, gathering three representatives of the young generation.

The two presentations from TEPCO addressed the important topic of the progress of the management of the damaged Fukushima Daiichi NNP in Japan.

- **Paper ID34 by J. Simon (Nigeria)** presented the challenges in developing nuclear power in Nigeria. The primary obstacle to developing nuclear power is reported to be the lack of technical expertise and experience in the management of SNF and radioactive waste. Although there has been an investment in nuclear science training, only 30% of trained individuals have gone on to gain nuclear experience. It is proposed to adopt a graded approach to address this issue through scaling to a bigger research reactor as a steppingstone to providing confidence to key stakeholders on national expertise in radioactive waste management.
- **Paper ID73 by F. Ledroit (France)** presented a process to ensure overall consistency of fuel cycle activities enabling to anticipate any modification or creation of facilities conducted by EDF together with Orano and Framatome. The ongoing development of an augmented expertise tool to support IRSN assessments and positioning on potential fuel cycle issues was described.
- **Paper ID151 by Y. Ishii (Japan)** presented an update on fuel removal activities from the at reactor pools of Units 1,2,3,5 and 6 Fukushima Daiichi NPP. Removal of fuel, both spent and fresh, stored in the spent fuel pools of each reactor building at the Fukushima Daiichi NPP is one of the important tasks to reduce the risk of releasing radioactive materials. An overview of the fuel removal project including recent progress and planning for the coming operations was covered.
- **Paper ID162 by K. Sawada (Japan)** presented the findings from investigations performed inside reactor pressure vessel and primary containment vessel of the damaged units at Fukushima Daiichi nuclear power station using muon and several remote operated devices. The status and planning of the complex programme of fuel debris removal was outlined.

Session 7.2 – Benefits of holistic approach to current and future fuel cycles

Session Chairs: Rebecca Tadesse (OECD/NEA) and John Simon (Nigeria/National Open University of Nigeria, YG Challenge Winner)

Session 7.2 comprised of five papers, one from Argentina, one from Belgium, one from Switzerland, one from France and one from Mexico.

- **Paper ID45 by L. Gringauz (Argentina)** presented the status of spent fuel management in Argentina. The scope of activities and facilities available in Argentina's nuclear industry were outlined and it was stated that the National Atomic Energy Commission is responsible for the management of radioactive wastes in Argentina. The presentation highlighted the need for comprehensively collating the data on spent fuel and subsequent utilization of the data to create a compelling narrative about the activities, facilities, strategies, and responsibilities regarding spent fuel management. This involves bringing together wastes generators (power plant) and waste managers together on a single communication platform to achieve a common understanding. A special note was made on the ongoing development of an information compilation tool, aiming at bringing alternative views and controversies about spent nuclear fuel in Argentina for public discuss.
- **Paper ID55 by L. Van den Durpel (Belgium)** presented the need to address the challenges in the nuclear fuel cycle with realistic short term economic implications. The complexity of deciding on a

spent nuclear fuel management option was emphasized, given the variety of available options. The sociopolitical effects, the absence of stable and tangible spent nuclear fuel and radioactive wastes management policy, storage solutions and evolving waste management requirements significantly impact the timeline and resources needed for the final radioactive wastes management solutions are also factors which add to this complexity. The Nuclear Real Options Model (NROM) was proposed as an assessment methodology to reduce cost and financial risk exposure for the various stakeholders in the nuclear fuel cycle. It considers fixed and ‘what if’ scenarios, uncertainties/probabilities in both timing and cost of options.

- **Paper ID74 by E. Vlassopoulos, (Switzerland)** presented a summary of the efforts being deployed in Switzerland to secure a general licence for a deep geological repository (DGR). The importance of simulation tools in providing a realistic representation of the spent fuel packaging process was emphasized, with special mention of an innovative tool called Repository Optimization Workflow (ROWO). This tool provides a holistic approach aimed at enhancing the planning and implementation of the DGR. The system is based on proxy modelling which models the various steps of the spent fuel handling processes and integrating the results into a single workflow. Pareto optimization analysis is then used to identify trade offs between better configurations of canisters and optimization potential, thereby enhancing the decision making process. The model will continue to be developed through the incorporation of new constraints, better accuracy, and validation.
- **Paper ID113 by C. Evans (France)** presented an assessment of multirecycling of spent nuclear in present and near future LWRs. Multirecycling was considered a viable interim option before the future deployment of commercial fast nuclear reactors. Feasibility analysis and fuel development studies have been conducted to assess reactor core performance with different configurations of MOX2 fuel assemblies. A 50% loading of MOX for multirecycling (MOX-MR) fuel can efficiently recycle plutonium from spent UOX and MOX fuels. Fuel cycle scenario simulations have also shown that multiple recycling scenarios can stabilize and reduce spent fuel storage needs and natural uranium resource requirements by over 20% and 40% compared to monorecycling and the open fuel cycle.
- **Paper ID116 by J.L. François (Mexico)** presented the status of spent nuclear fuel in Mexico, emphasizing the lack of a policy defining the nuclear fuel cycle in the country. This situation necessitates a study on spent nuclear management options to support future decision making on the back end of the nuclear fuel cycle. The presentation focused on a study that characterized spent fuel in terms of stock, composition, radiotoxicity, and heat load using the IAEA Nuclear Fuel Cycle Simulation System (NFCSS). The importance of optimizing multirecycling options and using recycled plutonium in MOX fuels was emphasized.

5. YOUNG GENERATION CHALLENGE

The #SFM24 Young Generation (YG) Challenge was conceived to increase participation in the conference by Young Professionals and Students. The Challenge call encouraged the submission of papers based on the seven Tracks of the Conference and also welcomed submissions relating to the conference scope.

24 Young Professionals submitted technical papers to the Conference and applied to the YG Challenge. These technical papers were peer-reviewed by the members of the International Scientific Programme Committee (ISPC) of the SFM'24 Conference. Although the number of winners was initially set at five, as indicated in the SFM'24 Conference announcement, the ISPC decided to award eleven winners (seven women and four men), due to the high scores of their papers, the diversity of topical areas as well as the geographical and gender balances.

Each of them co-chaired a technical session, together with a senior chair, and were tasked to prepare a draft summary of the technical discussions of their session (under the supervision of the senior chair) that have been included in these Proceedings.

The YG Challenge winners and titles of their submitted papers are listed in Table 5.

TABLE 5. YG CHALLENGE WINNING ENTRIES

Country	YG Challenge Winner	Paper Title
Egypt	N. A. Abdelwahab	Review on the Impact of Advanced Fuel Technology on the Radioactive Waste Inventory (Paper ID54)
Ethiopia	B. Kejela	The Challenges of Implementing Policies and Strategies for Handling Spent Fuel Waste Management (Paper ID12)
France	P. -E Dufour	A Tool to Estimate Isotopic Evolution for Actinides Transmutation Dedicated to Fast Molten Salt Reactors (Paper ID88)
France	H. Vincenti	Outlines for Building the Future of French Recycling Facilities (Paper ID61)
Mexico	D. Manrique	Towards a Sustainable Future: Deep Geological Repository for Nuclear Waste Disposal in Mexico (Paper ID130)
Nigeria	J. Simon	Addressing Nuclear Spent Fuel Management Challenges: A Key to Alleviating Nigerian Scepticism Towards Nuclear Power Generation (Paper ID34)
Poland	L. Bak	Transportation of Spent Nuclear Fuel Conducted in Poland - Lessons Learned (Paper ID32)
Russian Federation	E. Filimonova	Fundamental Approaches to HTGR SNF Reprocessing Technology Development (Paper ID7)
Sweden	V. Solans	Predicting Decay Heat by Combining Fuel Parameters with Gamma and Neutron Data Using Machine Learning (Paper ID38)
United Kingdom	A. Detkina	Advanced Burnup Credit Approach for the Storage of Boiling Water Reactors Spent Fuel (Paper ID126)
United States of America	M. Bell	Environmental Justice and Public Engagement in the US Consent-based Siting Process (Paper ID65)

6. CLOSING SESSION

6.1. CONFERENCE CHAIRMAN'S CLOSING REMARKS

Closing speech as prepared for delivery.

Jose Antonio Gago

Former General Manager, Asociación Nuclear Ascó – Vandellós II (*retiree*), Spain

Ladies and gentlemen, this was the 2024 Edition of the International Conference on Management of Spent Fuel from Nuclear Power Reactors, with a focus on Meeting the Moment.

Let me start my final address to you by thanking all the members of the International Scientific Programme Committee and the IAEA Secretariat, with a special mention to Amparo González-Espartero for her leadership and permanent smile, to Gerard Bruno, to Nancy and all the Conference services team, to Zsuzsanna, Simona, Nozha and Christoph, from the spent fuel management team. Thank you for your strong and invaluable support in making this Conference possible and for your endless efforts in taking care, before and everyday throughout this week, of every single detail, which has contributed to its success.

We have listened to **77** contributed oral presentations, visited **13** E-posters and **21** posters from **29** Member States and **2** international organizations, held **4** Panel discussions on National Programmes, Stakeholders Engagement, and Innovation and Integration, and **2** side events sponsored by France and the NEI, reflected in **101** peer-reviewed full papers that will be available in the Conference Proceedings, together with the summaries of the discussions during the different sessions. The conference covered all steps of the back end of the nuclear fuel cycle with particular attention being paid to managing spent fuel and wastes from SMRs.

So, Ladies and Gentlemen, what have we learned and what conclusions can we draw from our discussions over the last five days?

If we are to meet net zero carbon targets, nuclear will play an important role in the world's energy mix. In the opening addresses we were told that we had the attention of policy makers and now is the time for action. The subject of the fourth panel discussion and in the various sessions throughout the conference, the initiatives in support of SMRs, and in particular advanced reactor system back end fuel cycles, have been addressed in terms of the ability to store, transport, reprocess and dispose of the generated wastes. Most of these efforts are in the early stages but this provides us with the basis for developing strategies for making decisions on new fuel cycles.

We started this week by acknowledging the contributions of our young nuclear generation winners, who continued to actively participate in the conference through giving oral presentations, acting as co-chairs and having the opportunity to network with experienced professionals. The young nuclear generation is key to the implementation of a spent fuel management programme, as it is a major intergenerational undertaking.

We have been reminded that, regardless of the national approach or fuel cycle adopted, we need repositories to manage the waste arising from the fuel cycle whether this is technical, spent fuel or reprocessing wastes. During the week the contributed presentations and discussions on this topic have reassured us that this is being actively addressed, not only for existing, but also for potential wastes from new fuel cycles. The key cross-cutting message has been that this is a complex task to be done by a country alone. International cooperation to gain know-how, guidance and learning from existing and previous projects is invaluable. It is though, a time-consuming process and, therefore, early planning is essential.

Developing fuel cycles takes time. For those embarking on this process, there is over 60 years of learning to build on. In this regard we also heard about innovations throughout the back end of the fuel cycle, not only from a technological perspective but also in how we collaborate, such as going beyond sharing research to sharing infrastructures.

Having a DGR or other type of repository is only one piece of the puzzle, the necessity and benefits of accurate data, undertaking scenario analysis, technology developments to aid repository design, efficiencies, and safeguards are also required. We have heard about the various initiatives in these areas on spent fuel characterization, ongoing studies including spent fuel decay heat measurements to improve predictive models and the wider aspects of spent fuel and cladding characteristics.

While we as a community can deliver the technical solutions needed, we can only be successful in implementing them if we have social support and political commitment to do so. Continued political commitment and investment is key for the sustainable development of a nuclear programme. For example, we heard from France how they are developing their complete and comprehensive long term vision on the nuclear fuel cycle thanks to such support, as well as from Finland and other countries who are progressing towards operations at their DGRs in the coming decade.

The challenge of spent fuel management is not an urgency, but it is important to provide confidence to the public and other stakeholders that it is being consciously and safely managed. The subject of effective public engagement was the topic of our third panel discussion and has been an important conference topic. The panel has provided us with valuable insights into the approaches that have been taken in successful projects and with ongoing local liaison committees. We should all take this learning onboard and should look into how we can use this learning in our own work and projects.

We were provided by two young generation engineers from TEPCO with a brand new update on the status of spent fuel removal and fuel debris retrieval at the Fukushima Daiichi NPP and the progress made on this complex task.

At the opening session, we were reminded about the importance of considering transportation in our discussions as it is an essential enabler in all back end fuel cycle options. This morning, we heard that anticipation is key and planning for transport should start early to ensure we are in a position to smoothly transition from one stage to another.

I would like to thank again the IAEA secretariat in organizing and hosting such an excellent event, and the speakers in making this event successful through their insightful contributions. Finally, I would like to thank all of you for your open and honest participation in this Conference throughout the week.

With all that we have discussed, I would like to leave you with a question: **ARE WE MEETING THE MOMENT?**

Thank you for your attention!

6.2. INTERNATIONAL ATOMIC ENERGY AGENCY DEPUTY DIRECTOR GENERAL NUCLEAR SAFETY AND NUCLEAR SECURITY'S CLOSING REMARKS

Closing speech as prepared for delivery.

Lydie Evrard

IAEA Deputy Director General, Department of Nuclear Safety and Security

Dear Mr Gago Chair of the Conference, ladies and gentlemen,

It is an honour and it gives me great pleasure to provide closing remarks for the International Conference on the Management of Spent Fuel from Nuclear Power Reactors: Meeting the Moment.

I would like to take this opportunity to commend the excellent attendance at this conference with over 250 participants (including those participating virtually), from about 50 Member States, who have engaged actively to discuss a number of key topics in this subject area of importance.

As mentioned during the conference's opening session the subtitle of the conference 'Meeting the moment' is a message that can have varied interpretations and perceptions.

My understanding of 'Meeting the moment' — would be to rise to the occasion, especially in unexpected or challenging circumstances, to show courage, to make changes as needed, and to use our capabilities to the fullest extent, in a collaborative manner.

In this context, the Management of Spent Fuel from Nuclear Power Plants involves many dimensions.

Ladies and gentlemen,

In my capacity as Deputy Director General and Head of the Nuclear Safety and Security Department, I will focus more specifically on safety related matters in my remarks.

We are all living in a rapidly evolving environment, a changing landscape — and spent fuel management and related safety issues are no exceptions.

The conference clearly demonstrated that the technological environment is evolving, with an increased importance in the development of innovative reactors such as Small Modular Reactors — which has significant implications on the back end of the fuel cycle.

The conference also reflected the continued engagement to share extensive experience and comprehensive information about conventional reactors, including long term operations, and how to address the current and future corresponding implications on the back end of the fuel cycle.

In this context of an increased interest in the development of emerging technologies and this changing landscape, there is one important element: there is a common agreement and understanding that safe deep geological disposals will be needed for the safe long term management of spent fuel and radioactive waste.

The conference highlighted the wide diversity of national policies with regard to the status of spent fuel, and other uncertainties regarding the use of new technologies, which are:

- For some countries, spent fuel is an asset, used in reprocessing plants, allowing the re-use of nuclear material;
- For others, it is qualified as radioactive waste, to be directly disposed of;
- For some others, the national policy is not yet decided;

- Regarding new technologies, there are ongoing discussions about multirecycling for instance, but still some technical questions to be further explored.

The conference recalled the clear need to establish, as early as possible comprehensive national policies and strategies for the long term management of spent fuel, considering reference scenarios, and alternative or complementary scenarios as appropriate.

It goes without saying that the decision to reprocess spent fuel or not is an essential one, potentially impacting the timely development of geological disposal, and its footprint.

However, regardless of the decision on closed or open fuel cycle and despite uncertainties, the work on safe interim storage and on the development of a safe geological disposal for spent nuclear fuel and high level radioactive waste should actively continue because spent nuclear fuel and radioactive waste are here and need to be safely managed.

Ladies and gentlemen,

From a safety point of view, listening to the presentations and the discussions, which have focused on the management of spent fuel from existing and emerging nuclear reactors, I would like to underscore the following salient points:

- Minimization of waste remains an essential requirement, which is vital not only for existing reactors, but definitely should also be an objective for new types of reactors, and included as early as possible when a new reactor is being considered;
- In line with the characterization of waste and spent fuel, the importance of developing waste acceptance criteria for the facilities dealing with the management of spent fuel and radioactive waste needs attention, through the development of generic then specific safety cases;
- The safety implications of extended periods of storage and the consequences on the spent fuel status as ageing management and density of storage, have to be anticipated. This is of high importance for the subsequent management steps such as the transport and disposal of spent fuel. This was also highlighted during the 7th Review Meeting of the Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management in July 2022;
- Safe disposal is still the safe endpoint for waste management strategies, and the impact of new reactors or emerging technologies has to be addressed and anticipated;
- In this regard, there is a need for Member States to ensure full consistency between energy policies and nuclear spent fuel and radioactive waste management policies;
- The importance of taking into account the interdependencies between the different steps of the management of spent fuel and radioactive waste from existing as well as from emerging technologies. This is in line with the IAEA safety requirements on predisposal management of radioactive waste which indicate that the: “Interdependences among all steps in the predisposal management of radioactive waste, as well as the impact of the anticipated disposal option, shall be appropriately taken into account” [2];
- Lastly, in the context of management of spent fuel and radioactive waste from existing and emerging technologies, early dialogue and involvement of the different stakeholders such as industry, radioactive waste management organizations, regulatory bodies, local elected representatives as well as the public remains essential;
- I believe there is also a need for an engagement with Members of Parliament in an appropriate manner, for two main reasons. First, spent fuel and radioactive waste management are long term issues, generally addressed in national laws, and secondly, Members of Parliament have a direct connection to the general public in the districts where they are elected.

Ladies and gentlemen,

In addition to these main points of attention related to safety, I would also like to provide some details on the IAEA's support to its Member States with regard to safety of spent fuel and radioactive waste management.

The IAEA maintains a comprehensive series of safety standards for the safety of spent fuel and radioactive waste management. In addition, we ensure that the safety standards for existing nuclear technologies are also applicable or are revised to be applicable to the safe management of the spent fuel and waste arising from emerging technologies.

The Joint Convention on the Safety of Spent Fuel and on the Safety of Radioactive Waste Management is another key instrument, allowing Contracting Parties to share their experiences on their national programmes and to learn from others.

To highlight this vital aspect of learning from each other, during the country group sessions at the Seventh Review Meeting thirteen good practices were identified that included:

- The effective step by step licensing process for a spent fuel disposal programme;
- The socio-economic study of the deep geological repository to assess its long term added value for society; and,
- Entering a bilateral agreement (as a country with significant nuclear infrastructure) to receive, treat and dispose of small volumes of waste from a neighbouring non-nuclear country. The next Joint Convention review meeting will take place from 17 to 28 March 2025.

The Agency also offers the Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation (ARTEMIS), a peer review service for radioactive waste and spent fuel management, decommissioning and remediation programmes. Reviews can be organized for full radioactive waste and spent fuel programmes as well as for specific parts of programmes.

Dear Ladies and gentlemen,

To conclude:

I would like to extend my warmest congratulations to all of you on the success of this important weeklong conference. I would also like to take this opportunity to express my gratitude to the President of the Conference, Mr GAGO, for his steadfast leadership.

My sincere thanks to the Programme Committee who worked tirelessly over the past months, to the Scientific Secretaries Amparo and Gerard and all colleagues involved from NE, NS and MTCD Departments as well as others across the Agency who have been involved with the organization of this event.

I look forward to the lessons learned from the discussions this week and would like to reiterate the importance of keeping the momentum of organizing such international conferences at regular intervals.

The management of radioactive waste and spent nuclear fuel is crucial for the safe and sustainable use of nuclear technology at the national, regional and global levels; and the safe and sustainable management of these materials is vital for our future.

Thank you.

6.3. INTERNATIONAL ATOMIC ENERGY AGENCY DEPUTY DIRECTOR GENERAL NUCLEAR ENERGY'S CLOSING REMARKS

Closing speech as prepared for delivery.

Mikhail Chudakov

IAEA Deputy Director General, Department of Nuclear Energy

Dear Ladies and gentlemen, dear colleagues,

Good afternoon! I would like to start by expressing my appreciation for all those who made this conference such a resounding success.

To our Conference Chairman Mr Jose Antonio Gago, Session Chairs and co-chairs, opening session speakers, panellists, Young Generation Challenge winners, and all distinguished speakers– thank you. And thank you to Ms Nancy Herter, Ms Zsuzsanna Zohori, Ms Nozha Farjallah and Ms Simona Sandalova, as well as the rest of our colleagues from Conference Services and the Spent Fuel Management team who worked with you all so closely over the last few months. And of course, thank you to our Conference clerks and technicians who have ensured that everything runs smoothly.

Finally, I would like to thank the International Scientific Programme Committee and our scientific secretaries Ms Amparo Gonzalez Espartero and Mr Gérard Bruno for putting together such an informative programme. Your efforts are greatly appreciated. Meetings like this one are vital for ensuring continued progress in spent fuel management and enhancing the sustainability of nuclear power.

Ladies and gentlemen,

I understand that more than 250 participants from about 50 Member States as well as 4 international organizations have joined us this week in person and more than 200 registered to follow the conference online. This speaks to the high level of interest in this topic. Many interesting questions were posed throughout the sessions, and I am happy that there has been such an impressive level of engagement.

Building on the conclusions touched on by our Conference Chairman and my counterpart from the Department of Nuclear Safety and Security, I would like to focus on two main areas relevant to the ongoing work programmes within the Department of Nuclear Energy that were extensively covered this week.

The opening session emphasized the importance of the future generations of professionals in sustaining the nuclear power industry. To be sure, implementing a spent fuel management programme is a major intergenerational undertaking. Knowledge management is key as knowledge needs to be effectively communicated and transferred to the next generation. The IAEA is supporting Member States in capturing good practices and lessons learned and sharing information on specific topics relevant to the industry through organizing Conferences such as this one, developing and facilitating Coordinated Research Projects, assisting newcomers and publishing technical documents. We also recently published a guidebook on spent fuel storage options and systems which included information on technical storage solutions for both wet and dry storage systems. All of these initiatives help the IAEA in setting our work programmes and helping to ensure our programmes are aligned with the needs of Member States.

I am pleased to see that new reactor technologies such as SMRs, and the nuances of their fuel cycles, have been actively discussed throughout the conference. This is an area of particular interest to the Department of Nuclear Energy as significant efforts have been dedicated to these reactor types and the role they can play in helping the world reach net zero carbon emissions by 2050. Indeed, the conference has emphasized the need to take into account the full nuclear fuel life cycle, the impacts of decisions at the front end on the back end of the fuel cycle, and how new types of spent fuel will be managed. In addition, your discussions highlighted regulatory challenges, safeguards aspects, and stakeholder engagement.

You also discussed global efforts in developing and implementing technical solutions, and the need to continue moving ahead to make these technologies a reality. To this end, the Department of Nuclear Energy recently launched a new Coordinated Research Project on Challenges, Gaps and Opportunities for Managing Spent Fuel from Small Modular Reactors, which is aimed at building roadmaps for managing spent fuels from all envisaged SMR technologies.

Finally, I would like to join my colleague from the Department of Nuclear Safety and Security in reiterating the importance of this event as the only international conference worldwide entirely focused on the management of spent fuel from power reactors, a topic which remains as relevant today as it did when the first edition was held in 1987. Back in the 1980s, the challenge was providing sufficient reprocessing capacity and having limited experience and expertise in spent fuel dry storage. It is now business as usual and there are around 100 000 tonnes of spent fuel dry stored today. We have seen progress in moving ahead on stakeholder engagement to enable the implementation of disposal facilities for spent fuel and high level wastes and for siting new back end facilities. At the next conference on spent fuel management, we hope to be talking about operational deep geological repositories and SMR deployments. I look forward to seeing you at the next conference, where the latest challenges facing the nuclear industry will again be actively discussed.

Dear colleagues,

I hope you agree with me that this conference has provided a solid basis for continued progress in the safe, effective, and sustainable implementation of spent fuel management strategies. Indeed, we are ‘meeting the moment’ in this critical area — as this event has shown.

Once again, we look forward to seeing you at the next edition of this Conference.

I wish you all a safe journey home and declare the Conference adjourned.

Thank you.

7. CONCLUSIONS FROM THE CONFERENCE

1. The conference covered all steps of the back end of the nuclear fuel cycle with particular attention being paid to young professionals and the management of spent fuel and wastes from SMRs.
2. To meet net zero carbon targets, nuclear will play an important role in the world's energy mix. The initiatives in support of SMRs, and in particular advanced reactor system back end fuel cycles, have been addressed in terms of the ability to store, transport, reprocess and dispose of generated wastes. Most of these efforts are in the early stages but this provides us with the basis for developing strategies for making decisions on new fuel cycles.
3. Regardless of the national approach or fuel cycle adopted, repositories are needed to manage the waste arising from the fuel cycle whether this is operational, spent fuel or reprocessing wastes. Presentations and discussions on this topic reassured that this is being actively addressed, not only for existing, but also for potential wastes from new fuel cycles.
4. Developing fuel cycles takes time. For those embarking on this process, there is over 60 years of learning to build on. Innovations throughout the back end of the fuel cycle are essential, not only from a technological perspective but also in different collaboration ways, such as going beyond sharing research to sharing infrastructures.
5. Having a geological repository or other type of repository is only one piece of the puzzle, the necessity and benefits of accurate data, undertaking scenario analysis, technology developments to aid repository design, efficiencies, and safeguards are also required.
6. The challenge of spent fuel management is not an urgency, but it is important to provide confidence to the public and other stakeholders that it is being consciously and safely managed.
7. Technical solutions can only be successfully implemented if there is social support and political commitment to do so. Continued political commitment and investment is key for the sustainable development of a nuclear programme. Unfortunately, there is a lack of sustained political commitment in most of the countries, however there are some encouraging examples as the French comprehensive long term vision on the nuclear fuel cycle thanks to such support as well as the progress made in Finland and other countries towards operations at their geological repositories in the coming decade or so.
8. Transportation is an essential enabler in all back end fuel cycle options. Anticipation is key and planning for transport has to start early to ensure smooth transition from one stage to another.
9. Development and implementation of a geological repository is a complex task to be done by a country alone. International cooperation to gain know-how, guidance and learning from existing and previous projects is invaluable. It is though, a time-consuming process and, therefore, early planning is essential.
10. Young nuclear generation is key to the implementation of a spent fuel management programme, as it is a major intergenerational undertaking.

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- [2] INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of Radioactive Waste, IAEA Safety Standards Series No. GSR Part 5, IAEA, Vienna (2009).

ANNEX I: CONFERENCE STATISTICAL DATA

Prepared by Conference Services IAEA

International Conference on the Management of Spent Fuel from Nuclear Power Reactors – Meeting the Moment

Vienna, Austria
10–14 June 2024

Location	IAEA Headquarters, Vienna, Austria Board Room C
Scientific Secretaries	Amparo González Espartero (NEFW) Gerard Bruno (NSRW)
Scientific Support	Christoph Gastl (NEFW)
Admin. Support	Zsuzsanna Zohori (NEFW)
Conference Coordinator	Nancy Herter (MTCD)

REGISTRATION/ATTENDANCE

1) Total no. of official participants	293 including invited persons
From Member States	276 from 58 Member States
From Permanent Observers	0 from 0 Permanent Observer
From Organizations	17 from 6 Invited Organizations
Thereof Female participants	83 (28%)
Thereof Male participants	210 (72%)
2) Total no. of invited persons	56

PROGRAMMATIC INFORMATION

Structure	1 Opening Session with six opening statements 4 Panel Discussion 14 Technical Sessions from 7 Topical Tracks (77 Oral presentations) 2 Side Events 7 Poster Sessions (13 E-Poster and 21 Poster presentations) 1 Closing Session with three closing statements
Conference website	https://www.iaea.org/events/sfm24

Total number of official participants: 293

• **276 official participants from 58 Member States:**

Argentina	4	Lithuania	1
Armenia	1	Mauritania	1
Austria	1	Mexico	3
Bangladesh	2	Namibia	1
Belarus	1	Netherlands, Kingdom of the	3
Belgium	6	Nigeria	2
Brazil	1	Norway	2
Canada	8	Pakistan	2
China	4	Paraguay	1
Comoros	1	Poland	2
Congo	2	Romania	2
Czech Republic	2	Russian Federation	34
Egypt	6	Saudi Arabia	5
Eswatini	1	Singapore	1
Ethiopia	3	Slovakia	1
Finland	6	Slovenia	1
France	28	Spain	19
Germany	16	Sudan	1
Ghana	4	Sweden	4
Hungary	4	Switzerland	7
India	3	Tajikistan	1
Indonesia	2	Türkiye	2
Iraq	1	Uganda	1
Italy	1	Ukraine	3
Japan	6	United Kingdom	18
Jordan	3	United Republic of Tanzania	2
Kenya	1	United States of America	22
Korea, Republic of	13	Yemen	1
Libya	1	Zambia	1

• **17 official participants from 6 Invited Organizations:**

Electrical Power Research Institute (EPRI)	1
EUROPEAN UNION (EU)	3
International Organization for Standardization (ISO)	1
OECD Nuclear Energy Agency (NEA)	3
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ANNEX III: LIST OF ABBREVIATIONS

10B	Boron-10 (used in control rods for neutron absorption)
ADS	Accelerator-Driven System
AGR	Advanced Gas-cooled Reactor
AMR	Advanced Modular Reactor
ANCCLI	Association Nationale des Comités et Commissions Locales d'Information (France)
ANLWR	Advanced Non-Light Water Reactor
ARTEMIS	Integrated Review Service for Radioactive Waste and Spent Fuel Management, Decommissioning and Remediation (IAEA)
ASN	Autorité de Sûreté Nucléaire (France)
ASOF	Advanced Separation for Optimum Management of Spent Fuel
BARC	Bhabha Atomic Research Centre (India)
BWR	Boiling Water Reactor
CANDU	CANada Deuterium Uranium
CEA	Commissariat à l'Energie Atomique et aux Energies Alternatives (France)
CIGEO	Industrial Centre for Geological Disposal (France)
CLI	Commissions Locales d'Information (France)
CNDP	Commission Nationale du Débat Public (France)
CNEA	Comisión Nacional de Energía Atómica (Argentina)
CNSC	Canadian Nuclear Safety Commission
CNL	Canadian Nuclear Laboratories
COVRA	Centrale Organisatie Voor Radioactief Afval (Netherlands)
CRIEPI	Central Research Institute of Electric Power Industry (Japan)
CTS	Centralized Temporary Storage
DPC	Dual Purpose Casks
DGR	Deep Geological Repository
DOE	Department of Energy (USA)
DOT	Department of Transportation (USA)
DU	Depleted Uranium
EBR	Experimental Breeder Reactor
EC	European Commission
EDF	Électricité de France
ENRESA	Empresa Nacional de Residuos Radiactivos S.A. (Spain)
EPRI	Electric Power Research Institute
ERDO	Association for Multinational Radioactive Waste Solutions
ERU	Enriched Reprocessed Uranium
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
FBR	Fast Breeder Reactor
FBTR	Fast Breeder Test Reactor
FDP	Funded Decommissioning Programme (UK)
FNPP	Floating Nuclear Power Plant

FOAK	First of a Kind
FR	Fast Reactor
FSC	Forum on Stakeholder Confidence (NEA)
FSMSR	Fast Spectrum Molten Salt Reactor
GDF	Geological Disposal Facility
GNEP	Global Nuclear Energy Partnership
HAEA	Hungarian Atomic Energy Authority
HALEU	High-Assay Low-Enriched Uranium
HHGW	High Heat Generating Wastes
HLLW	High Level Liquid Waste
HLW	High Level Waste
HTGR	High Temperature Gas-cooled Reactor
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
ILW	Intermediate level waste
IMO	International Maritime Organisation
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France)
ISAC	Innovative System for Actinide Conversion
ISF-1	Interim Spent Nuclear Fuel Wet Storage Facility (Ukraine)
ISF-2	Interim Spent Nuclear Fuel Dry Storage Facility (Ukraine)
JRC	Joint Research Centre (European Commission)
KAERI	Korea Atomic Energy Research Institute
KSFDS	KANUPP Spent Fuel Dry Storage (Pakistan)
LEU	Low Enriched Uranium
LLRW	Long Lived Radioactive Waste
LWR	Light Water Reactor
MIRA	Multinational Infrastructure for Managing Radioactive Waste
ML	Machine Learning
MNR	Multinational Repository
MOX	Mixed Oxide Fuel
MOX2	Second-generation Mixed Oxide Fuel
MSR	Molten Salt Reactor
MVDS	Modular Vault Dry Storage System
NDA	Nuclear Decommissioning Authority (UK)
NEA	Nuclear Energy Agency (OECD)
NEI	Nuclear Energy Institute (USA)
NGO	Non-Governmental Organization
NPP	Nuclear Power Plant
NPS	Nuclear Packaging and Services
NRA	Nuclear Regulation Authority
NRC	Nuclear Regulatory Commission (USA)
NTS	Nuclear Transport Solutions (UK)
NWMO	Nuclear Waste Management Organization
NZN	Net Zero Nuclear

OECD	Organisation for Economic Co-operation and Development
PAEC	Pakistan Atomic Energy Commission
PDCA	Plan Do Check Act
PFBR	Prototype Fast Breeder Reactor
PHWR	Pressurized Heavy Water Reactor
PIE	Post Irradiation Examinations
PIRT	Phenomenon Identification and Ranking Tables
PNGMDR	Plan national de gestion des matières et des déchets radioactifs (France)
PNNL	Pacific Northwest National Laboratory (USA)
PNRA	Pakistan Nuclear Regulatory Authority
PPD	Package Performance Demonstration
PURAM	Public Limited Company for Radioactive Waste Management (Hungary)
PUREX	Plutonium-Uranium Reduction Extraction
PWR	Pressurized Water Reactor
R&D	Research and Development
RAM	Radioactive Materials
RCT	Ring Compression Test
RD&D	Research, Development, and Demonstration
RD&I	Research, Development and Innovation
RepU	Reprocessed Uranium
SCC	Stress Corrosion Cracking
SDG	Sustainable Development Goals
SFISF	Spent Fuel Interim Storage Facility
SFM	Spent Fuel Management
SFP	Spent Fuel Pool
SFR	Sodium-cooled Fast Reactor
SKB	Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering Aktieföretag, Sweden)
SMR	Small Modular Reactor
SNF	Spent Nuclear Fuel
TEPCO	Tokyo Electric Power Company
TNPP	Transportable Nuclear Power Plant
TRU	Transuranic
TRISO	Tristructural-Isotropic (fuel type)
TSO	Technical and Scientific Support Organization
UAE	United Arab Emirates
UCS	Universal Canister System
ULF	Used LWR fuel
UNF	Used Nuclear Fuel
UOX	Uranium Oxide
URL	Underground Research Laboratory
VVER	Water-Water Power Reactor (voda-vodyanoi energetichesky reaktor, Russian Federation)
WAC	Waste Acceptance Criteria

WG	Working Group
WIPP	Waste Isolation Pilot Plant
WISARD	Waste Integration for Small and Advanced Reactor Designs
WNA	World Nuclear Association
WNTI	World Nuclear Transport Institute
YGE	Young Generation Event

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