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Proceedings of the Workshop on the Management of Spent Fuel, Radioactive Waste, and Decommissioning in SMRs/ Advanced Reactor Technologies

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7-10 November 2022

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Radioactive Waste Management Committee

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes;

– to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

Foreword

Small modular reactor (SMR) technologies are gaining interest as countries seek to reduce carbon emissions while maintaining energy security. For these new technologies to be deployed in a timely manner, the management, storage, transport and disposal of their radioactive waste needs to be closely examined at the early design stage. This is a question upon which the international nuclear and radioactive waste management community, particularly the Nuclear Energy Agency (NEA), are placing increasing focus.

The NEA and Natural Resources Canada (NRCan) organised an international workshop on 7-10 November 2022 on the implementation of radioactive waste management and decommissioning strategies in light water and Generation IV SMR technologies. The goal of the workshop, which took place in Ottawa, Canada, was to devise a guideline document that can help implementers understand key issues in the decommissioning and waste management of new reactors from the design perspective, aiding in the licensing process and in future decommissioning and waste management activities.

This report captures the outcome of this workshop. It was approved by the NEA Radioactive Waste Management Committee (RWMC) on 7 June 2024.

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List of abbreviations and acronyms

AECL	Atomic Energy of Canada Limited (Canada)
AMR	Advanced modular reactor
ARPA-E	Advanced Research Projects Agency-Energy (DOE)
CANDU	Canada Deuterium Uranium (Canadian Reactor Design)
CDLM	Committee on Decommissioning of Nuclear Installations and Legacy Management (NEA)
CEA	Alternative Energies and Atomic Energy Commission (Commissariat à l'énergie atomique et aux énergies alternatives, France)
CNL	Canadian Nuclear Laboratories (Canada)
CNSC	Canadian Nuclear Safety Commission (Canada)
CRL	Chalk River Laboratories (Canada, owned by AECL and operated by CNL)
DGR	Deep geological repository
DOE	Department of Energy (United States)
EPA	Environmental Protection Agency (United States)
GDF	Geological Disposal Facility
GWe	Gigawatt electrical
HALEU	High assay low-enriched uranium (fuel)
HLW	High-level waste
IAEA	International Atomic Energy Agency
ILW	Intermediate-level radioactive waste
LEU	Low-enriched uranium (fuel)
LILW	Low- and intermediate-level radioactive waste
LLRW	Low-level radioactive waste
LWR	Light-water reactor
M^3	Cubic metres
Magnox	Reactor type designed to run on natural uranium with graphite as the moderator
MOX	Mixed oxide (fuel)
MSR	Molten salt reactor
MWt	Megawatt thermal
MWe	Megawatt electrical
NB Power	New Brunswick Power (Canada)
NEA	Nuclear Energy Agency

NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission (United States)
NRCan	Natural Resources Canada (Canada)
NWMO	Nuclear Waste Management Organisation (Canada)
NUREG	Nuclear Regulatory Commission Publications (United States)
OECD	Organisation for Economic Co-operation and Development
OPG	Ontario Power Generation (Canada)
PWR	Pressurised water reactor
R&D	Research and development
RWMC	Radioactive Waste Management Committee (NEA)
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
SMR/AR	Small modular reactor/advanced reactor
SMR/ART	Small modular reactor/advanced reactor technologies
SNF	Spent or used nuclear fuel
$T_{1/2}$	Half-life
TRISO	Tristructural isotropic (fuel)

Executive summary

As countries explore ways to reach their decarbonisation targets while meeting energy demand, many are focusing on light water and Generation IV small modular reactors (SMRs) as potentially useful technologies. To ensure these technologies are viable to complement existing energy sources, the management, storage, transport and disposal of the radioactive waste needs to be closely examined at the early stages of the design process.

The Nuclear Energy Agency (NEA) and Natural Resources Canada (NRCan) organised in 2022 an international workshop on the implementation of radioactive waste management and decommissioning strategies in light water and Generation IV SMR technologies. The event took place in Ottawa, Canada on 7-10 November 2022.

This workshop explored the types of light water and Generation IV SMR technologies, the potential for fuel recycling (closed fuel cycle) and work that is being conducted in relation to design and fuel concepts. The scope of the workshop was wide-ranging, covering technical, legislative and social perspectives. The event reviewed potential strategies for the management and disposal of operational and decommissioning wastes and how specific wastes from these streams might be accommodated.

Advanced reactors and advanced fuels offer a wide range of scenarios for back-end management. It is essential to design the back end of the fuel cycle, which includes the management and disposal of radioactive waste, decommissioning and the recycling of used nuclear fuel, from the beginning in order to optimise final disposal volumes by minimising waste volumes and reusing valuable materials. However, there is limited experience with the recycling and disposal of some fuel types and waste forms, though decisions on investments in reactor technologies already appear imminent. Moreover, waste acceptance criteria for disposal are based on current fuel designs, and thus new spent fuels may necessitate additional research to ensure they can meet existing requirements. Each country must assess concepts in relation to its existing waste management options, and there may be a need to extend existing disposal capacities or to develop new disposal facilities.

There should be early dialogue between the designers, regulators, operators and other stakeholders to address information needed on SMR design and waste characteristics. This information is required so the waste management and decommissioning community can assess the types and volumes of waste forms that might be generated in order to evaluate how existing practices can be adopted or modified to allow for safe storage and disposal of both operational and decommissioning wastes.

Clear government policy and licensing requirements as well as early engagement with the public and Indigenous communities, including the need for informed consent, were highlighted as key drivers for the deployment of SMRs.

Other key takeaways discussed during the workshop include the need for a better understanding of:

- SMR design and nuclear fuel characteristics;
- transport cask design (for SMRs with 5% and higher enrichment of ^{235}U);
- spent fuel (including TRISO fuel) and waste management (including graphite);
- fuel treatment options including recycling options.

There is a major role for waste management organisations and safety authorities to prepare for the future. Back-end constraints should be considered to contribute to decisions on the SMR technologies to be deployed and on the associated fuel cycle options.

Please refer to the workshop summary in Chapter 6 (Session 5) for more information.

1. Introduction

The 2022 workshop organised by the NEA and NRCan on the implementation of radioactive waste management and decommissioning strategies in light water and Generation IV SMR technologies convened participants from various fields of expertise in radioactive waste management, decommissioning, nuclear science and development, transportation and community outreach, including young professionals in these areas. The goal of the workshop was to devise a guideline document that will serve implementers in understanding the key issues in decommissioning and waste management of new reactors from the design perspective, aiding in the licensing process and future decommissioning and waste management activities.

1.2. Objectives

The objectives of the workshop were:

- To better understand how radioactive waste management and decommissioning should be considered as part of a more comprehensive preparation for the deployment of these reactors from the design stage.
- To understand unique features of SMR waste and the key questions that need to be answered to ensure a clear path to final disposal.
- To review current challenges in decommissioning and provide lessons learnt.
- To better integrate educational institutions and engage with interested communities early in the process.
- To better understand how the current regulatory framework should be considered in the early development of SMRs.

The three-day workshop consisted of four main sessions, with a fourth day dedicated to a site visit. The workshop sessions were sequenced to first address the various design features of SMRs and then build off the first session to cover the storage and transportation as well as waste management and decommissioning implications of these new technologies. Considering stakeholder engagement is pivotal for the successful deployment of SMRs, the last session focused on this topic and invited representatives from the Indigenous community and other stakeholders to close the workshop. The topics and speakers for each session were carefully selected to address and share information related to one aspect of anticipated waste management and decommissioning activities that could potentially be impacted by deployment of SMRs. This report captures key elements of each session.

1.3. Opening remarks

The workshop was opened by the conference Chair, James McKinney, who welcomed all participants to the workshop. Elder Thomas Louttit of the Moose Creek First Nation also provided welcoming comments and an opening ceremony.

Introductions were provided by NRCan, the NEA, the Canadian Nuclear Safety Commission, the US Department of Energy, the Nuclear Waste Management Organisation (Canada), Poland’s National Atomic Energy Agency, the US Nuclear

Regulatory Commission (NRC) and the French Alternative Energies and Atomic Energy Commission (CEA):

- Natural Resources Canada observed that Canada sees significant potential in SMR technology and has initiated the SMR Action Plan. Funding has been provided to support research into SMR wastes and a CAD 970 million loan has been provided to OPG to allow production of the first SMR. The NWMO is proceeding to select a site for a used fuel disposal facility, to be announced in 2024. He recognised that Indigenous engagement is crucial and noted the Indigenous advisory council of the SMR Action Plan. He noted that Canada has made significant strides in looking at SMR technology.
- The NEA noted that Finland is on track to have the first operating repository and that there is great uncertainty with SMR technologies. They come with questions such as: types of fuel, how to manage transport, how to dispose of the fuel and how to ensure legacy waste is not left to future generations.
- The CNSC presentation focused on collaboration and regulatory change. This includes regulatory harmonisation and a need to harmonise licence requirements and standards and streamline the regulatory approval process. Additional funding has been provided by the Canadian government to implement such change. In relation to deep geological repositories, it was noted that the government must streamline the process of implementing geological disposal. Questions that must still be addressed are plans for decommissioning, whether waste will be acceptable for repositories, and the strategies for management, transport and disposal of used nuclear fuel. Going forward, transport will be one of the main issues to be addressed. In addition, with respect to reprocessing, a policy decision from the federal government is required on that issue. With respect to Indigenous consultation, federal legislation was adopted on the rights of Indigenous peoples. There will be many challenges to be more transparent and streamlined, and to adopt more open processes and to promote inclusively.
- The DOE provided an update on implementing a new integrated waste strategy. The DOE is: identifying gaps in storage, transport and disposal; investigating effects of extended storage on used fuel integrity; investigating different geologies for disposal concepts; developing cost estimates for disposal strategies; and investigating the handling of wastes from light water and Generation IV SMR technologies. Interim storage of used nuclear fuel away from interim storage at the reactor sites is a topic under consideration as the DOE is not actively pursuing a disposal site at this time. Consent-based siting is now also being looked at. The DOE has provided a funding opportunity to investigate ways to implement consent-based siting, to further develop a consent-based siting process and to define a broader strategy for an integrated waste management system.
- The NWMO provided an overview of its activities in siting a deep geological repository (DGR) for used nuclear fuel in Canada. The NWMO is working through a process that will result in finding a location that is both geologically appropriate and supported by an informed and willing host community. In relation to Indigenous engagement, the NWMO has been on a journey of reconciliation, and this year has published the first reconciliation report. The deep geological disposal repository is being designed to protect people and the environment and provide a safe place for Canada's used nuclear fuel. In relation

to advanced reactor technologies, the NWMO is currently working with SMR vendors to investigate potential future waste types.

- Poland's National Atomic Energy Agency provided a review of Poland's nuclear programme. As for many countries, Poland is planning on developing a repository for its nuclear waste. A more detailed presentation on Poland's nuclear programme follows in Chapter 4 (Session 3).
- The US NRC provided an update on its activities associated with advanced reactors and the evolving landscape of new nuclear energy. Please note that the following data was reported during the 2022 workshop and it can be surmised that the information has changed since then. At that time, the NRC was preparing for an increase in advanced reactor licensing as over 17 vendors were actively engaged in pre-application activities. It was expected that there would be over 13 applications for licences by 2027. Forty-three topical reports and white paper reviews were completed for seven vendors and there were thirty-six topical reports and white papers under review from eight vendors.
- The French Alternative Energies and Atomic Energy Commission (CEA) provided a detailed presentation on the potential future energy systems being considered in France and other countries. He noted that in key European countries, people want nuclear power as part of their energy mix (even in Germany and Italy) and that modular reactors could allow a flexible response to the local network demand. The fight against climate change has been identified as the most significant factor driving this opinion. The main difficulties related to nuclear waste include waste disposal, recycling, lifetime of the wastes, transport and volume of waste produced. Current disposal concepts are designed for wastes from existing power reactors and are not at this stage designed for new reactor concepts. This applies to back-end activities associated with potential reprocessing activities. SMRs can provide an additional solution to constructing future energy mixes, but waste disposal and recycling are key issues that should be addressed as soon as possible.

2. Session 1 - Understanding the functioning of major light water and Generation IV SMR technologies and fuel cycles

Session 1 focused on understanding the functioning of light water and Generation IV SMR technologies, with the main differences expected in the function of the technologies and mode of operation (e.g. fuel type) compared with contemporary designs. It also will explore the key questions designers need to consider when developing a new fuel that has not been evaluated by waste acceptance criteria. Summaries of these presentations are provided below.

2.1. Overview of mature light water and Generation IV SMR technologies and associated fuel types

This session focused on understanding the functioning of major light water and Generation IV SMR technologies, with the main differences expected in the function of the technologies and mode of operation (e.g. fuel type) compared with contemporary designs.

The session Chair Massimiliano Fratoni began with an introductory presentation on SMRs. He explained that they were generally less than 300 MW(e) and that the reactors were similar in that, unlike current power reactor designs, they are constructed in modules. There are currently 83 SMR concepts in development.

There are four main SMR concepts world-wide that use enriched uranium fuel (other fuels could be considered as well such as Pu-based fuels and for many concepts a closed fuel cycle is envisioned):

- **Molten salt.** This concept uses a molten liquid fuel (fluorides or chlorides) containing from 5 to 20% enriched uranium. The concept is considered an open cycle, allowing for continuous refuelling and fission products removal. The challenges include the pre-disposal management of the used fuel salt, and that the salt in its native form is not stable for ongoing waste management.
- **Liquid metal.** In this concept, the reactor is cooled by lead or sodium. The fuel is enriched from 15 to 20%, with a long refuelling cycle of up to 30 years. There are multiple fuel forms and coolant activation of the sodium or lead can be a challenge.
- **Gas cooled.** In this concept, fuel is enriched from 8 to 20%. The concept makes use of a pebble bed design and allows for a 2 to 5 year refuelling cycle. The coolant is helium, and this design allows for open or closed fuel cycles. While anticipated to have high thermal efficiency, the requirement for graphite and graphite activation can be a challenge.
- **Water cooled.** This design is related to the pressurised water reactors currently in use, with fuel enrichment of up to 5%. It allows for longer fuel cycles with a fuel life of about 2 years. With the similarity of this fuel to existing fuel types, this concept is most compatible to existing used fuel waste management facilities.

In summary, the concepts that are being developed have many features and challenges. Water-cooled SMRs are the most compatible designs with existing waste management facilities, while other concepts would require more specialised waste management and disposal facilities.

2.2. Key attributes of light water and Generation IV SMR fuel types and design considerations and implications for decommissioning and radioactive waste management

This session explored the key questions designers need to consider when developing a new fuel that has not been evaluated by waste acceptance criteria. For example: Are deep geological repositories capable of taking this kind of waste? Should that be considered now? What challenges/issues may arise that are different compared to traditional reactor oxide fuels during transportation, management and disposal of used fuel or by-products of used fuel treatment (recycling/conditioning)?

Ultra Safe Nuclear Corporation's reactor concept

This presentation focused on the reactor concept being proposed by Ultra Safe Nuclear Corporation. This concept makes use of a fully ceramic microencapsulated fuel pellet (TRISO). These pellets are stacked and placed into a graphite fuel block. As the fuel is oxide-based, it is anticipated that it would be mostly compatible with existing waste management and proposed disposal facilities.

It allows for easy assembly (85% assembly costs at factory) with a reported short construction time. Demonstration reactors are planned for CRL in Ontario, Canada and at the University of Illinois, United States.

In relation to used fuel waste management, there are three operational components: storage, transport and disposal. Although removal of the fuel pellets from the graphite fuel block may be possible, the concept being proposed is transport, management and disposal of the graphite fuel block including the fuel pellets.

The presentation identified the following challenges:

- Regulatory variability and uncertainty complicate the development of a complete end-to-end fuel management pathway for all SMR developers.
- Offsite interim storage will be necessary for remote SMR operations.
- The waste fee structure, acceptance structure and performance criteria will significantly impact used fuel management.

During the presentation, it was noted a gap existed in relation to transport that the vender needs to consider. The presenter was also asked if the cask is being considered for storage and whether these would be commercially available. The presenter responded that they are currently engaged with commercial cask providers.

Takeaways

- This design is suitable for direct disposal in DGRs either as loaded graphite fuel blocks or consolidated fuel pellets.
- Material properties of the fuel design provide significant protection in DGR environments without other considerations.

- A clear and rational basis for the waste fee structure, acceptance criteria, performance criteria and resolution of regulatory gaps considering used fuel management timelines is needed.

Natrium advanced reactor fuel cycle management

This presentation focused on the Natrium advanced reactor and its fuel cycle management. The Natrium advanced reactor concept is a sodium fast reactor with a molten salt energy island. An application for a construction licence for a demonstration plant is planned for 2023. Once a demonstration plant becomes operational, a commercial series I and a larger commercial series II design are anticipated. The Natrium demonstration reactor is expected to provide between 345 and 500 MWe. The design is based upon prior US experience with molten salt research reactors.

Technology improvements with this design are associated with improvements in the fuel. The fuel is a uranium metal annular fuel with a helium filled central pore, replacing the previous uranium zirconium fuel with a sodium bond. The fuel is initially planned to contain up to 19% enrichment, with planned fuel advances by 2050 reducing this to 10%, and after that using natural or depleted uranium.

It is anticipated that it will be a once-through fuel cycle with a cycle length of 18 months. Used fuel management anticipates storage in the reactor vessel for 1.5 years and 10 years in a used fuel pool prior to dry storage. With more advanced fuel containing no enrichment, it is anticipated to have a cycle length of 22 months and a residency time of 40 years.

Challenges remain in the areas of disposal and transport. In relation to disposal, it is anticipated that with the appropriate engineered barriers and administration controls, used fuel can be placed in deep geological repositories. Key challenges include metal fuel vs oxide, higher specific radionuclide inventory, higher specific decay power, cladding materials and regulatory approvals. In relation to transport, it is felt that as challenges in disposal are addressed, they can be applied to transport challenges.

During the presentation, comments related to minimising waste volumes generated from this SMR and studies that have been conducted in a repository environment that are favourable towards disposal were highlighted.

The need for a storage transport package that can be used in the repository environment and the desire to eliminate the need for repackaging was also discussed.

Takeaways

- The Natrium reactor uses a once-through fuel cycle trending towards higher burnups and resulting in reduced used fuel by mass and volume.
- Technical challenges can be resolved with appropriate engineered barriers and administrative controls allowing for disposal in deep geological repositories.
- The licensing basis will conservatively assume 100% radionuclide release on engineered barrier breach.
- Fresh fuel transportation casks have to be licensed for fuel with higher fissile content and different assembly shape/size.

Terrestrial Energy work on molten salt design waste stream

This presentation focused on Terrestrial Energy's work on the Integral Molten Salt Reactor's waste stream. This reactor is of the molten salt design and accommodates both secondary and tertiary (non-nuclear) molten salt loops for thermal and electric energy transfer. The reactor vessel contains both graphite and fuel at a nominal 2% enrichment, with makeup fuel at 5% enrichment. Although there could be some processing of used fuel, it is anticipated to be a once-through fuel cycle. The waste stream (molten salt fuel) generates off-gas, and after shutdown, the fuel would be left in the reactor for a residence time of 6 to 12 months. There would be almost no tritium generation.

The focus of Terrestrial Energy's current work on waste management has been on molten salt fuel. The current plan is for used fuel salt to be conditioned into a durable, long-term waste-form and stored within a deep geological repository as implemented per the NWMO's Adaptive Phased Management structure.

Terrestrial Energy states that it is preferable to condition the used fuel salt rather than store in its original fluoride state due to reactivity with water and its potential for radiolysis.

Terrestrial Energy has engaged with the Australian Nuclear Science and Technology Organisation to explore use of their ceramic-glass composite waste form, Synroc (or synthetic rock), for used fuel salt.

The Synroc process can be described as a three-step process intended to place radionuclides in mineral phases analogous to naturally occurring phases by means of elevated temperatures and pressures akin to geological conditions. This is achieved by mixing wastes with chemical additives to form a ceramic, calcining at elevated temperatures to form the ceramic and hot pressing of calcined waste to reduce waste volume while also applying a tight-fitting metallic seal to allow for simplified transport and handling.

The audience asked whether the used molten fuel would need to be transported in order to condition the waste. The response was that the whole conditioning process would be conducted on-site and that nothing would need to leave the facility.

Takeaways

Work on assessing the viability of conditioning the molten salt fuel is ongoing. Bench-scale synthesis, microstructural characterisation, and leach testing of the Synroc waste-form is presently being planned for the target glass-ceramic in order to demonstrate:

- a set of chemical additives to produce a calcinable and pressable powder;
- leaching resistance of the conditioned waste-form under static and semi-dynamic conditions;
- bounds for waste loading in terms of mass and volume;
- bounds for incorporation of additional neutron absorbers;
- a non-uranium-bearing waste-form simulant to facilitate future development of processing equipment.

Fuel cycle considerations for Generation IV reactors being developed in New Brunswick, Canada

This presentation focused on New Brunswick Power’s interest in advancing to Generation IV reactors. Three streams were identified: readily deployable SMR at Darlington by the late 2020s, on grid advanced SMRs developed in New Brunswick for deployment in early to mid-2030 and micro reactors for small communities and resource extraction.

Two technologies were identified for stream two, the ARC-100 design (to be deployed at the Point Lepreau generating station) by 2030 and a Moltex SSR-W by the mid-2030s:

- The ARC100 design is a 100 MWe non-pressurised pool reactor with inherent safety characteristics and passive safety features. It would have a 20-year fuelling cycle and could recycle its used fuel. It would be ideally suited for electricity and superheated steam for hydrogen or synthetic fuel production.
- The Moltex SSR-W, (Stable Salt Reactor – Wasteburner) is a 300 MWe non-pressurised pool reactor that is fuelled online and can be fuelled by used CANDU fuel. It has inherent safety characteristics and passive safety features. Its benefits are related to high-level radioactive waste disposal, and it provides superheated steam for hydrogen or synthetic fuel production. Its proposed deployment at the Point Lepreau site is expected in the mid-2030s.

Disposal considerations include issues of sodium bonding, in-container criticality, fuel durability and out of container criticality and radionuclide transport/dose. Conditioning of the fuel prior to disposal may not be necessary but has benefits, but with a significant cost which may lead to an early reprocessing decision.

With respect to Moltex Fuel, a facility would be required for recycling or reprocessing which would remove and concentrate transuranics. Principle waste streams from such a facility would be UO_2 (bulk of waste from CANDU fuel) and a small, concentrated volume of fission product salt waste, which would require an above ground extended cooling period. Disposal considerations would require used fuel containers that may have to be modified to a more durable form. This may not be necessary but has some benefits (deep borehole disposal may be a better option).

During the presentation, the following comment was received. If DGRs are going to be decentralised in Canada, then technologies such as this may be considered in western Canada. Otherwise, transport of used fuels must also be addressed.

A question related to decision-making and the regulatory environment was asked. The presenter responded that in Canada there is a requirement for an environmental assessment. For advanced reactors this becomes more challenging as questions that must be answered include: where the used fuel will be stored, how it will be stored and how it will be transported. The presenter also noted that discussions must be held in advance in order to have more realistic timelines. On one hand this is not yet treated as a project, yet it is considered a project in relation to the impact assessment. Conducting an impact assessment greatly extends timelines, and in comparison to other industries it is not a level playing field. This needs to be reconsidered by policy makers.

Takeaways

- Used fuel in the future will be more diverse than just uranium oxide type fuels.
- Reprocessing/recycling has advantages and should be seriously considered.

- Repository designers need to be more flexible with waste acceptance criteria and safety case results versus imposing existing margins and characteristics of uranium oxide fuel. This includes consideration for disposal in deep boreholes.
- If SMRs are decentralised, then more regional disposal facilities will be required; otherwise, long-distance transport of used fuel to a centralised disposal facility would be required.
- Approvals of radioactive waste disposal facilities need to be on a more level playing field in comparison to other industries if climate change objectives are to be met.

Westinghouse lead fast reactor – design and waste management overview

The presentation provided an overview of the Westinghouse lead fast reactor, its core design and fuel cycle options, lead management and review of its main waste streams.

The design is described as a simple, compact and robust modular-construction pool-type reactor, with enhanced passive safety, fuel cycle flexibility typical of fast reactors and a balanced approach between advanced designs and existing designs to enhance performance and marketability. The reactor design considers thermal energy storage and heat dissipation to the atmosphere, through air-cooled condensers. No water bodies are required in the vicinity of the plant. Used fuel can be transferred directly to cask, with no requirement for in vessel storage or water pool storage. The coolant is cheap and abundant and easier to handle (when unirradiated) than other advanced reactor coolants.

^{14}C is generated and its specific activity after 1 000 years of cooling is ~1 Ci/kg of used fuel or, ~20% of the total used fuel specific activity. An assessment of carbon retention in a repository environment must be performed to ensure a viable path for geologic disposal. ^{15}N enrichment is also being investigated to improve fissile use and would also reduce ^{14}C generation.

In relation to lead management, non-radioactive lead can be managed in accordance with existing regulations for toxicity. Radioactive lead, as a result of activation of lead and contaminants during operation would have a comparable activity to sodium 20 years after plant shutdown. Contaminated lead purification technologies can reduce residual lead activity and simplify disposal or recycling.

Takeaways

- Lead as a coolant has several favourable attributes that motivated Westinghouse’s selection of this design as its next generation of nuclear power plants. These attributes are further strengthened by selected plant design choices that benefit overall safety and economics.
- There is a need for geologic disposal of used fuel (open cycle) or vitrified high-level waste (HLW), as for current and advanced reactors.
- Past experience and analysis with oxide fuel disposal can be leveraged for the core design options.
- Fuel will require a specific assessment to ensure disposability due to its higher dissolution rate and ^{14}C generation.
- Extensive experience in using liquid lead in laboratories and test facilities from Westinghouse partners can be used to inform lead management.

- Development of lead management and lead waste handling/disposal strategies is in progress. Multiple options are possible and will be further evaluated to establish the best trade-off.
- Early engagement with regulators is beneficial and will continue to be sought in the future.

Design considerations for waste minimisation and decommissioning optimisation

This presentation focused on design considerations for waste minimisation and decommissioning optimisation. For SMRs, it was noted that the core surface to volume ratio is 2 to 3 times higher than that for existing reactors and that there would be more neutron leakage. Additionally, there would be lower burnup compared to current power reactors and that new generation reactors would work in more demanding environments.

Common characteristics of SMRs include simplification by modularisation and integration, underground construction for enhanced security, seismic and passive safety systems, multi-module plant layouts and better learning curves.

However, modularisation of reactor components may be a major determinant in decommissioning, factory fabrication, reuse, repair, replacement and recycling.

The audience asked if there is a possibility of standardisation of the back end. The presenter thought that would be difficult as various technologies are being considered. The audience also asked how many variables and parameters there are to consider. The presenter responded maybe a hundred but also noted that most of the reactors have yet to be built, so more information will be available in the future.

Takeaways

Pros and cons of decommissioning were highlighted.

Pros included:

- less absolute volume of decommissioning waste;
- lower uncertainty in radiological characterisation;
- transportable reactor components;
- more effective decontamination possible;
- small components size facilitates material removal;
- faster learning curve;
- modularity;
- possible in-factory decommissioning;
- integration in modules may facilitate full scope decontamination.

Cons of decommissioning included:

- different fuels with varying enrichment and chemical stability so there is no “one size fits all” approach;
- co-location of facilities for non-electric applications;
- integration of components in-core may produce more activated materials;

- enhanced neutron leakages (bigger reflector required or higher enrichment);
- lower fuel burnup.

2.3. Panel discussion on key takeaways and recommendations

The presenters were invited to continue to discuss their key takeaways/recommendations as well as address questions from the audience. The discussion covered a wide range of topics and centred on issues such as timelines, regulation, packaging, design and public interaction.

Timelines

With regards to the timelines for developing waste management strategies of the various waste forms expected to be generated from new technologies, it was deemed by some members of the audience that the timelines mentioned in the presentations were rather too optimistic, as the licensing process for a DGR took over 30 years to demonstrate the capabilities of licensees' understanding of the interaction of waste forms (HLW and vitrified waste) with underground and surface environments and there is still much more work that is required in order for the process to be fully completed (especially related to vitrified glass [ceramics] waste forms; the industry is still working on demonstrating the safety of glass).

The panelist acknowledged that there is still much more work that needs to be done and challenges that will need to be closely examined but noted they felt that there is an appropriate balance between the sentiment of optimism and confidence to address the outstanding work that remains. However, the panel asserted that the remaining work should not hinder the industry from continuing its efforts to examine and apply lessons learnt from past studies (in both LWR and advanced reactor fuel management) to address the challenges. The following are a few additional points noted:

- To qualify waste for disposal for a particular geological repository, the following elements are needed:
  - detailed geological surveys;
  - underground laboratories; and
  - spent fuel performance characteristics and behaviour.
- The variability and uncertainty associated with the very long life span of the fuel management introduces major challenges for management of the back end of the fuel cycle. This time span brings into question the solubility and the forms of the chemicals that could take over geological time, all of which have to be accounted for. Probability safety analysis is typically used to assess the performance of the fuel over a long time period.
- In the case of vitrified waste management, although there are no specific repository considerations that can be used to plan for management strategies now, vendors can use broad academic and peer-reviewed bases for the material performance of silicon carbide and graphite to make a broad statement about their performance in the long term that are likely to hold even if the industry is still learning more about vitrified waste management. There will always be continuing learning with a long-time horizon. The technical challenges are easy to solve; the hard part is implementation.

Regulation

Questions pertaining to the way in which regulators could consider performance criteria for fuel forms, or fuel classes, were raised by the audience. It was noted that regulators needed to provide more clarity regarding this issue. It was also noted that regulations should not be developed for every type of new reactor and that there should be some standardisation.

Inquiries were also made by members of the audience with regard to the level of pressure that had been exerted on the regulators as repository development is a policy decision through a government action, and vendors needs to know there is a repository in order to address some of the public's questions related to the entire fuel cycle including spent fuel management strategies.

The panel noted that a two-way dialogue between the vendors and the regulators is encouraged. Commercial entities and regulators may have differing opinions, but it is important that all parties endeavour to seek clarity as they both have similar views on safety.

- With respect to the exertion of pressure on the regulators, certain members of the audience/panel believed that not enough has been done apart from the attempts to encourage regular conversations. However, the issue may not be at the technical level but rather at the policy level and finding a site for disposal. By way of illustration, the length of time that a facility will operate is often ruled by policy and the regulator is not able to rush this review process.
- With respect to the policymakers in Canada, it was noted that there is good dialogue between the vendors and regulators. The regulator and NWMO have both been available for early dialogue regarding the vendor's vision. This workshop further helps to nurture the channels of communication between parties.

The panellists acknowledged that although existing regulations may be functional, enhancements are still needed as engineering and science have had the time to focus on SMR design.

- In order to have an implementable solution for the back end of the fuel cycle (either for individual fuel forms or fuel classes), vendors will need to have a better understanding of:
  - The waste fee structure – what are the regulatory requirements related to paying for disposal of the fuel?
  - The waste acceptance criteria – what condition will be acceptable by regulators and waste management organisations?
  - The performance criteria that need to be met to have licensable/disposable fuel form.

Packaging

In relation to packaging, the audience discussed the advantages of a universal package as well as the essential elements that might be needed to make a package universal, including incorporating the requirements of a disposal package into the design. The panel expressed a range of viewpoints, noting the following:

- Although a standardised package is a great idea, it may be difficult to design based on the varying types of fuel that are expected to be used.

- Detailed information on disposal facility boundary conditions, which are not yet available, would need to be well understood in order to advance with package design considerations, such as dose rate limits and changes in disposal volume needed to meet dose rate limits.

Design

The audience noted that there appear to be many restrictions concerning the potential to reuse major reactor components as a means to reduce waste volumes and minimise disposal and storage requirements. The question as to what extent the recycling of components could be implemented for SMRs was raised by the audience. The panellist noted the following:

- Opportunities for the industry to be responsible and consider the reuse and recycling of components as a general concept was noted. Especially for the intermediate-level waste, the industry should try to understand the potential waste forms and the kind of preprocessing of that waste that can be achieved in order to minimise the volume of waste that will need to be disposed of. This strategy can ultimately be cost-effective in the long run; however, it will require upfront industry collaboration and shifting how things are done now in order to repurpose the components/materials for different applications (e.g. what to do with the resins, steam generator tubes) to maximise sustainability and minimise waste.
- Efforts are being made by the industry to reduce, reuse and recycle. Some recognised recycling options include recycling zirconium. However, the economic aspect associated with these recycling efforts can be financially challenging as recycling metals can lead to cost that may be ten times the initial costs. Additionally, recycling often leads to a generation of new low-level waste volumes.
- From a commercial perspective, the cost of recycling/reprocessing technology and the size of the market would need to be more favourable in order for recycling to be a viable option for a vendor. Fuel security and future demand that must be met in order to reach net zero and recognising the pressure this demand is going to put on uranium can also drive the need for recycling/reprocessing. Moreover, recycling cannot be applied to all fuel types, thus disposal options are still required. This is an aspect that should be taken into account during the design stage.

Public interaction

Questions regarding public engagement and the kind of topics of most interest to the public were raised. Below are the main takeaways of this discussion:

- The public mostly needs assurance. As a result of proactive and transparent consultations, the public acceptance of nuclear power has been on the rise as the public is now aware and has a better understanding of waste forms.
- Engagement can take place in two ways – locally and through the regulatory outreach process. Locally, the interaction tends to be positive, and the discussions are mostly focused on the project itself, safety, storage and understanding the new material that will be used and less about long-term disposal. As an example, in New Brunswick, many positive conversations

related to waste management have taken place with both the Indigenous community and the general public. Special interest groups, using social media as one platform, can play a negative role in diverting the conversation as local storage or disposal of radioactive waste is a prospect that the public does not want to entertain.

- In Canada, the Indigenous community and the public have taken positive notes of this level of engagement and respect. It was noted that the Canadian Nuclear Safety Commission has made great efforts to ensure that information is made available. The Canadian Nuclear Waste Management Organisation has additionally made significant efforts with regard to its communication with the public and Indigenous peoples.
- The panel further noted that public meetings hosted by regulators may not always result in a positive conversation as people with a different agenda attend the meeting to derail the conversation.
- The panel highlighted Saskatchewan Power’s judgement of public opinion using focus groups as one approach that seemed to provide much more benefit in delivering a constructive dialogue among participants about nuclear power.

3. Session 2 - Storage and transportation of spent fuel and radioactive waste in light water and Generation IV SMR designs

The second session highlighted the challenges associated with fuel storage and transportation and their potential applicability to new fuel types. It also addressed the feasibility of reprocessing fuel from new designs, noting the different types of reprocessing techniques, including associated waste generation and economic feasibility. Summaries of presentations under this session are captured below.

3.1. Overview of work activities on fuel storage and transportation

This session highlighted the challenges associated with fuel storage and transportation and their potential applicability to new fuel types (e.g. dual cask, criticality issues and environmental concerns). It began with a presentation by the NEA.

Ad-hoc Group on Extended Storage and Transportation of Spent Fuel and Radioactive Waste

This presentation focused on the NEA's Radioactive Waste Management Committee (RMWC) Ad-hoc Group on Extended Storage and Transportation. Extended safe storage is an interim solution currently anticipated to cover timescales around 100 years as an expected baseline practice. Much longer timescales of more than 300 years can also be considered in some circumstances.

The ad-hoc group was created by the NEA RWMC in March 2021. Its objectives were to: review and analyse available information on extended storage and transportation; identify gaps and topics needed to be developed further; evaluate if existing codes and model capability predict radioactive waste and used fuel evolution during long-term storage; and to develop proposals to the committee on areas for further development. The group wrote a report to capture its findings related to topics to further address in the areas of extended storage and transportation of radioactive waste and used fuel. These topics were recommended as a starting point for the identification of the committee's goals for the future.

The audience asked questions related to experiences of good public engagements and if there are any milestones identified. The presenter noted that success is achieved if engagement is delivered, if it is delivered in the correct manner and if it has positively affected the public mood in five years. In terms of milestones, there are no milestones defined yet and more work is needed in this area.

Takeaways

- The various topics identified by the group reflect the different perspectives of extended storage. Some of them are technically specific issues while others would require more generic consideration. The key topic able to incorporate all other topics was identified as sustainability of extended storage and transportation, whereby sustainability is considered in the context of the whole waste programme and its wider optimisation. This topic is recommended to the committee as a general direction for future development.

- Clarity with respect to the endpoint of storage is needed as storage is an interim stage of waste management. It is necessary to identify the purpose and duration of waste storage. Radioactive waste storage can be a challenge due to different policies or national strategies. There is a need to ensure that extended storage does not create a new legacy and is connected to the next planned steps of waste management (transport and disposal for example).
- In the environmental area, the need to understand the packaging and containment requirements of different waste forms from both technical and safety points of view is essential. There is a range of waste types that require different packaging approaches. Therefore, it is necessary to consider the extended storage of various waste streams and their requirements for packaging to ensure safe, long-term storage.
- From the point of view of stakeholder confidence, the need to address the main challenges of seeking public acceptance of the extended storage concept is advised.
- In the economic area, the group prioritised the robustness of the storage concept and the cost of storage including all operations. There is a need to consider the possibility of repackaging approaches for extended storage periods.

International Atomic Energy Agency (IAEA) ongoing activities on challenges of and opportunities for SMR spent fuel management

This presentation focused on the IAEA's ongoing activities in relation to SMR used fuel management. Types of SMR technology include land-based water-cooled reactors, marine-based water-cooled reactors, liquid metal-cooled fast neutron reactors, micro reactors, molten salt reactors and high-temperature gas-cooled reactors. Each type of reactor has an associated nuclear fuel cycle. Used fuel challenges are closely related to nuclear fuel designs.

Nuclear fuel cycle challenges and considerations for land-based water-cooled reactors include the design of fuel assemblies (half the length of the ones used in conventional PWRs with no major changes in construction and material), enrichment levels, transport and storage solutions (recertification or new developments are needed) and, as for all new developments, licensing procedures tend to be slow:

- For marine-based water-cooled reactors most data are not publicly available.
- High-temperature gas-cooled reactors have limited back-end experience.
- Liquid metal-cooled fast neutron reactors have some operational experience, but new fuel types introduce a new fuel chemistry.
- Micro reactors that use TRISO or uranium silicide fuel have no on-site fuel handling issues but challenges include transport of the fuelled or used reactor to or from the site.
- Molten salt reactors use halide fuel salts (chemical hazards, corrosion), fuel processing requires large facilities and recycling of halide salt mixtures and management of salt mixtures containing all fission products are challenging.

There are many activities on SMRs and related applications in four departments (Nuclear Energy, Nuclear Safety and Security, Technical Co-operation and Safeguards) of the IAEA. Member states are requesting consistent, co-ordinated, and optimised agency support for SMR development and deployment. The IAEA published an SMR platform brochure and conducted a technical meeting on the back end of the fuel cycle, which occurred in September 2022. There were 110 participating experts from 34 member states and 3 international organisations resulting in 40 presentations and extended abstracts.

Takeaways

- Understanding the implications of the different stages for managing SMR used fuels (including transportation) is paramount to making informed decisions on the SMR technology to be deployed and on the associated fuel cycle option.
- Characterising SMR used fuels is key to anticipating challenges/gaps/opportunities for their management.
- Integrating the selected used fuel management strategy for a given SMR technology with the one already implemented is important.
- Transportation applies to all stages of the nuclear fuel cycle and is content specific (new package designs and regulations will be needed).
- International collaboration is essential.
- The IAEA has launched an SMR platform to provide national governments, experts and regulators with support on all aspects of SMR development and oversight.

Transport challenges in the nuclear fuel cycle: learning from experience

This presentation focused on the challenges of transporting nuclear substances. Transport has a record of decades of safe and secure delivery with no significant release events.

Currently, there are over 20 million shipments annually. The transport sector remains a critical enabler to the nuclear industry, but it is not always recognised as such.

The industry response to COVID-19 has been positive with continued operations (fuel and waste moves continue) but medical isotopes and radiopharmaceuticals remain challenging. Transport demands are growing. Increases are seen in both the front end (fresh fuel and new nuclear technologies) and the back end (used fuel and waste).

Geopolitics and malevolent actors are changing the threat environment (not just physical protection but also technology, supply chain, cyber, etc.). New technologies, new actors and geopolitics are driving a need for change in hardware, security, routing, sector skills, policy and regulation, and global acceptance and public perception.

Takeaways

- Transport remains a critical enabler of nuclear energy, both in countries with nuclear energy and those embarking on new nuclear energy programmes. However, some regulations are disproportionate, and transporters are leaving the sector. There is a need to find a balance. Agility and consistency in modern regulation is required.
- Collaboration is needed across the industry to advance transport technology, safety and security. Knowledge management is vital. There is a need for engagement and education of stakeholders and the sector needs to be focused on future demands.

Opportunities to optimise recycled used fuel management in the United States

This presentation focused on research being conducted in support of used nuclear fuel recycling and storage/disposal. Interest in decarbonisation and reliability is likely to create new used fuel management opportunities.

Optimising the value of nuclear feedstock should be considered as future reactors may recycle used nuclear fuel to extract even more energy from uranium. New reactor startups will be using new fuel and between six and nine reactor suppliers may be able to power them with used fuel. Most recycling strategies would not separate out plutonium.

Recycling would not replace the need for fuel disposal in a geologic repository, but recycling technologies should further clean energy and sustainability goals. Recycling should increase the economic competitiveness of future nuclear reactors and help improve energy security. The United States should support research, development and demonstration of used nuclear fuel recycling technologies, but they should avoid unacceptable proliferation risks. The regulator should license recycling facilities under its current regulations and implement innovative approaches to achieve timely reviews of recycling facilities.

Existing US reactors are reimbursed for their used fuel storage costs by the federal government in accordance with contracts signed in 1983 and future reactor owners will have to carry all used fuel storage costs for the life of the plant under an amended standard contract. The US electricity marketplace will drive further innovation.

Initiatives include the DOE awarding USD 38 million for projects leading to used fuel recycling (11 recipients with a diverse range of process and technology development projects). In relation to canister design, UPWARDS is a USD 3.6 million, 3-year project sponsored by the DOE’s Advanced Research Projects Agency-Energy (ARPA-E) that will support advanced reactor development by establishing a universal canister design and waste form acceptance criteria for the disposal of advanced reactor waste streams.

Takeaways

- The United States has expanded research into the potential for spent fuel recycling and canister design associated with advanced reactor designs.

Advanced non-light water reactors: integrated waste management system considerations and challenges

This presentation focused on integrated waste management system considerations and challenges. Since there is less experience and knowledge in managing advanced reactor fuels, basic types of reactor concepts were provided.

Fluoride salt-cooled high-temperature reactors

Considerations for this type of reactor fuel are similar to those for the gas reactors except the TRISO spent fuel pebbles will likely need to be washed before placing them into a dry storage canister. The final storage option of a graphite fuel element may differ if the reactor uses prismatic fuel.

Sodium-cooled fast reactors

Some plans use sodium-bonded uranium-zirconium metallic fuel clad in stainless steel. This fuel form and cladding material have a long history of research and development and were demonstrated in the Experimental Breeder Reactor-II. Sodium-bonded fuel may need to be treated prior to disposal because it is generally considered unsuitable for direct disposal. An alternative fuel is annular, sodium-free, binary uranium-zirconium metallic fuel clad in stainless steel. This advanced fuel design is expected to enable the high burnup required for breed-and-burn operation.

Lead-cooled fast reactors

The majority of designs will use clad ceramic fuels similar to light-water reactor fuel. These reactors will likely use uranium oxide, plutonium dioxide, or nitride ceramic fuel pellets with < 20% enrichment inserted into stainless steel cladding and backfilled with helium. Fuel pins are then inserted into square or hexagonal fuel assemblies.

Multiple agencies and organisations have responsibility for managing used nuclear fuel in the United States:

- The EPA sets radiological protection standards.
- The utilities/operators site, design and submit licence applications, including an environmental report, in accordance with requirements established by the NRC. They construct and operate reactors in accordance with the NRC licence. They are responsible for the management and storage of all used fuel until accepted by the DOE.
- The NRC prepares an Environmental Impact Statement for the proposed reactor and conducts a review of the licence application, including any required hearings.
- The DOE is responsible for managing and disposing of used fuel it accepts under the Standard Contract as required by the Nuclear Waste Policy Act of 1982.
- The NRC regulates interim storage and permanent disposal and certifies SNF transportation casks.

Takeaways

- US regulations for managing SNF are well established and applicable to advanced reactors. Research, development and demonstration of technologies for all aspects of the back end of the nuclear fuel cycle is needed both to inform future decisions and to implement the used fuel management strategies chosen.
- Near-term activities for the management of advanced reactor used fuel are required for fuels and waste forms including activities such as treatment, transportation, interim storage, disposal, recycling and integration.
- Planning for an integrated waste management system for advanced reactors is important. Experience in managing used fuel generated by the current fleet of reactors shows that decisions made in isolation can result in sub-optimal solutions with respect to the entire waste management system. An integrated waste management system analysis is necessary to understand all possible options, approaches, and strategies to inform all stakeholders and guide future decisions.

3.2. Technical and economic feasibility of reprocessing radioactive waste, as well as storage and transport of reprocessed fuel, based on reactor type (closed-loop fuel cycle)

This session addressed the feasibility of reprocessing fuel from new designs, noting the different types of reprocessing techniques, including associated waste generation and economic feasibility. It began with a presentation from the NEA Expert Group on Fuel Recycling and Waste Technology.

The NEA Expert Group on Fuel Recycling and Waste Technology and options for future fuels recycling

This presentation focused on the activities of the NEA Expert Group in Fuel Recycling and Waste Technology. In it, the choice of the fuel cycle should be assessed in the context of sustainability (open vs. closed cycles).

Key questions for new nuclear reactors included: efficient use of uranium resources, and how to safely manage wastes, assure non-proliferation and maximise the economic benefits of nuclear. There is no particular nuclear fuel cycle option that satisfies all issues perfectly and there is no consensus about the best approach to manage used fuels.

There is a large and increasing accumulation of used nuclear fuels in storage. Recycling saves natural uranium resources and the back end makes only a small contribution to the environmental footprint. Recycling minimises the lifetime and volume of high-level wastes. Closed fuel cycles lead to higher levelised costs of energy than open fuel cycles, but uncertainty ranges overlap (NEA, 2013).

The main objectives of the expert group on fuel recycling and waste technology are to perform technical assessments of separation processes in applications related to current and future nuclear fuel cycles and to recommend collaborative international efforts to further development and deployment.

Recent and current activities include:

- Report on treatment of volatile fission products (ready for publication).
- International review of reuse and recycle of components from used fuels (publication expected in 2023).
- International Database of Extractant Ligands (data review in progress, first release foreseen in 2024).
- Benchmark on simulation codes for solvent extraction (launched in 2021, first phase in progress).
- New activity on the chemistry of molten salt reactor fuel cycles (joint activity with the IAEA).

The audience questioned how ^{129}I and ^{36}Cl can be addressed. The presenter responded that the repository safety case is required to consider these isotopes. One aspect that must be reviewed is the waste form and its stability.

Takeaways

- There is no consensus on what the best approach is to manage used nuclear fuel.
- The choice of the fuel cycle should be assessed in the context of sustainability.

- There is an important role for international collaboration (NEA Expert Group Fuel Recycling Waste Technology).
- There remain options for new innovative recycling technologies (examples include advanced PUREX and grouped actinide extraction).
- There is a need for a range of options for used fuel management from SMRs.

Considerations for recycling of small modular reactor fuels

This presentation focused on the potential for recycling of SMR fuels. There are a variety of concepts under development globally, but most international experience is with low-enriched uranium oxide fuel (LEU). These fuels are often selected for reactor designs, followed by TRISO, molten salt and metal. Many reactor designs use HALEU fuel, but the supply has been identified as a significant near-term challenge. Some designs have more adaptability for recycled fuels (some molten salt reactor designs propose fuels based on transuranic elements recovered from discharged fuel).

It is difficult to predict deployment success for the many potential fuel forms; fuel cycle management options are necessary for the major options.

Many SMRs would discharge higher-value fuel (HALEU-based fuels have the potential to alter the economic perspectives of recycling). The US recycling research programme is focused on the development of fuel recycle options with improved proliferation resistance, improved economics and reduced waste volumes.

Some SMRs could enable modified fuel cycles (molten salt reactors have a "simple" fuel form that could lend itself to fuels created from leaching used fuel). US research programmes have some activities on fuel synthesis and fission product management, as well as the consideration of fuel properties.

There are many potential technology options to recycle nearly any fuel, but the selection of an optimal fuel cycle technology depends upon many factors, especially the resulting recycled fuel form. While the United States has the disadvantage of no existing infrastructure for the recycling of commercial fuel, this also provides flexibility to optimise for the shape of future US reactor deployments, and new programmes are developing broad options.

Advanced reactor fuels (not including oxide forms) that have chemically reactive materials may be difficult to directly dispose of, e.g. sodium-bonded fuels (in this case, fuel recycling or a thermal treatment for sodium removal may be required). Used molten salt fuels may require chemical conversion or stabilisation prior to disposal. In some cases, radiolysis, ground water solubility, or chemical reactivity with water may create challenges for certain repository environments. TRISO fuels are generally considered to be chemically very stable (however, some forms are also very high volume, and there may be microbial concerns in some repository scenarios).

A recent paper claims that SMRs will produce more waste per unit of energy than current reactors. However, there are many assumptions and variables that make scenarios difficult to compare. There is a similar situation for wastes resulting from recycling. Repository inventories are limited by a combination of mass, heat load, volume and exposure rate. There is uncertainty in required cooling times for recycled fuel and its resulting waste forms. High-level wastes from recycling of different fuels are highly dependent upon the repository location and the policies of the host nation (required waste form chemistry can vary significantly). Recycling processes should minimise waste form volume and the number of waste form processes.

In relation to recycling waste forms, borosilicate glass for wastes derived from aqueous processes are mature. However, active development is ongoing for improved capture and disposal options for semi-volatiles, such as iodine. A baseline sodalite-based ceramic waste form has been established for salt wastes, but development is ongoing for a waste form that converts from a halide to oxide form.

A question was asked if the DOE only evaluates viable options. The presenter responded that the agency currently looks at all options, but it does have this discussion frequently.

Takeaways

- There are many types of SMRs under consideration and it is easiest to organise them according to fuel type. It is difficult to predict deployment success for the varied fuel forms and fuel management options are needed for those under consideration.
- HALEU-based fuels provide a potential improvement in economics, especially if coupled with simplified processes.
- The selection of optimal fuel cycle technologies depends on many factors, especially the resulting recycled fuel form.
- High-level wastes from recycling different fuels may create a challenge for disposal in repositories. For existing or planned repositories, the kinds of high-level waste that may safely be disposed of is dependent upon the safety case for the repository to contain that specific waste. Policies of the host nation may also be a factor.
- Discharged salt fuels may require chemical conversion or stabilisation prior to disposal.
- There is not enough information yet to make any decisions.

Reprocessing fuel from AMRs: A focus on fast chloride molten salt reactors

This presentation focused on fuel reprocessing from molten salt reactors with the goal of moving towards the complete closure of the fuel cycle. It focused on the La Hague plant (France) that has addressed back-end challenges for used fuels for 50 years. A broad range of fuels have already been processed at this facility and after 30 years of operations ageing issues such as corrosion and clogging have already been addressed. However, with new fuel, new issues will need to be solved.

Since 2019, the potential for recycling molten salt reactor fuels has been explored. For metallic wastes the challenge is to maximise the lifetime of reflector bricks. The main approach is to convert the used salt to be acceptable in a reprocessing plant; however, containers to transport fresh and used salt have yet to be designed.

The audience asked if there is any intention to recycle molten salt at La Hague. The presenter responded that recycling molten salt is a good idea, but further research is needed as it is possible, but complex.

Takeaways

- Preliminary calculations show promising trends in the reduction of volume and long-term radiotoxicity of waste when using fast chloride molten salt reactors in combination with a reprocessing plant.

- Compatibility with the La Hague facility to recycle molten salt needs to be fully assessed but at this point there are no showstoppers. New workshops would need to be conducted.
- The objective is to contribute to the realisation of a prototype in the next decade.

Strategies for processing TRISO nuclear fuel

This presentation focused on the potential for processing used TRISO nuclear fuel.

TRISO fuel is designed for high-temperature gas-cooled reactors. There is renewed interest in this reactor design, but it will likely generate 25 times more spent nuclear fuel than light-water reactors per ton of fuel. Neutron activation of graphite impurities leads to ^{14}C accumulation in the blocks/pebbles, which needs to be addressed.

Early approaches focused on actinide recovery:

- 1975 – A process using combustion to separate graphite from particles resulted in uncontrolled release of ^{14}C. This was then followed by a mechanical process to grind and crush particles to expose the fuel. This was an intensive use of mechanical equipment resulting in maintenance and reliability issues.
- 1982 – A process using combustion was used, but the carbon was captured in a calcium hydroxide scrubber. This resulted in controlled dumping of calcium carbonate on the ocean floor.
- 1992–- Mechanical separation of fuel from graphite blocks using special tools. Graphite could be disposed of as low-level radioactive waste (LLRW).

21st century approaches to processing TRISO:

- Mechanical operations typically impact process plants' reliability, availability and cost effectiveness (as capabilities are needed for remote maintenance and repair).
- Technologies researched today are therefore non-mechanical.
- Early tests should be conducted with surrogates and confirmed with limited tests using actual used nuclear fuel. Surrogate design should be able to account for the projected and desired processing characteristics of actual used nuclear fuel with the specific technology being considered.

Criteria for technology selection include robustness, adaptability, integration for actinide recovery, hazard control, waste management, ease of technology maturation up to pilot scale and engineering for remote operations.

Takeaways

- Criteria for technology selection include robustness, adaptability, integration for actinide recovery, hazard control, waste management, ease of technology maturation up to pilot scale and engineering for remote operations.
- Several promising approaches to processing TRISO exist.
- Current economics do not support actinide recovery.
- Possible options for management of wastes from advanced fuel cycles and reactors are under increasing consideration (integrated waste management).

- For further details, see report PNNL-32969 at www.osti.gov/search/semantic:pnnl-32969

Incorporating spent fuel, radioactive waste and decommissioning needs into the design of SMRs

This presentation focused on the eVinci microreactor. This design provides 5 MWe with a minimum 8-year refuelling cycle. It is transportable both for installation and removal of used fuel, cost-competitive, operates with minimal onsite personnel, is a mature technology and provides high speed load following capability.

In comparison to decommissioning large scale nuclear facilities that are not designed for dismantling (difficult access, hazardous environment, underground structures) this microreactor is designed with dismantling in mind (factory built, factory disassembly, factory refuelling, refurbishment and recycling).

The eVinci design allows for both waste retrieval and processing. The design allows for commercial scale retrieval of ^{14}C from its graphite core.

A comment was received that spoke to implications for licensing, since there would be two separate facilities, one for manufacturing and another for decommissioning, and both would require licensing.

Questions were raised by the audience relating to the presence of iodine in graphite, managing the graphite if the TRISO particles fail and if an assessment was done on the economics of reprocessing. The presenter responded that the presence of iodine was considered but the issue has not been resolved yet and technology deployment is not expected until 2028. With respect to fuel failure and graphite, TRISO is contained in fuel rods, and they also act as containment. Graphite would likely be disposed of as intermediate-level waste. In relation to the economics of fuel reprocessing, the presenter responded that it is cheaper to dispose of fuel rather than to reprocess it.

Takeaways

- This reactor design is described as transportable both for installation and removal of used fuel, is cost-competitive, operates with minimal onsite personnel, is a mature technology and provides high speed load following capability.
- It is designed to be dismantled (factory built, factory disassembly, factory refuelling, refurbishment and recycling) and allows for both waste retrieval and processing.

Analytical chemistry and waste characterisation

This presentation focused on analytical chemistry and waste characterisation. The presentation began with an overview of the Kinectrics organisation and the North American Young Generation in Nuclear organisation, which provides opportunities for a new generation of nuclear enthusiasts to develop leadership and professional skills.

Kinectrics' work in radioanalytical chemistry was described. It was noted that since there are no current SMRs, there are no samples to analyse, but the same method development principles can apply to give an idea of the hazard of a sample (and therefore a system). This is important when radioisotopic concentrations cannot be calculated. Applications include environmental surveying, dosimetry uptake events and radioactive waste.

Scientists must validate theoretical data with empirical data, and this will also apply to SMRs. There will be a lot of speculation about which isotopes will be present. With respect to zirconium, zircalloy is used to make pressure tubes, calandrias, etc., due to its ability to withstand corrosion and due to its low cross section. During irradiation, some of the stable Zr is activated to ^{93}Zr, which has a half-life of 1.5 million years, so its concentration in comparison to other isotopes will increase over time which then becomes a factor for placement in a repository.

ORIGEN software may be used to estimate ^{93}Zr activity of certain components (i.e. pressure tubes), but if it is going into a repository environment the data must be correct. A few challenges with ^{93}Zr are that it is a beta-only emitter, and it is not a common element for separation. There is not much literature information and no standard reference information. Consequently, Kinectrics developed a robust and specific method to detect ^{93}Zr in various matrices. It is the only commercial lab in the world to offer this analysis. The results for pressure tube samples are on the same order of magnitude as ORIGEN calculations, although a little bit lower than expected.

The audience asked if Kinectrics is doing research to prepare for SMRs. The presenter responded that Kinectrics is more responsive than proactive, but once samples are submitted for analysis, they will be investigated.

Takeaways

- Kinetrics has developed analytical capability to detect ^{93}Zr in various matrices.
- Kinectrics will conduct research into nuclear materials in response to vendor requests.

3.3. Panel discussion on key takeaways and recommendations

The presenters were invited to continue to discuss their main key takeaways/recommendations as well as address questions from the audience. The discussion touched upon a range of topics including interim storage and retrievability, reprocessing, and repositories.

Interim storage and retrievability

The audience discussed matters pertaining to intergenerational equality, environmental issues and inherited responsibility, given that the timescale of interim storage is around 100 to 300 years. The panel noted that storage options need to be developed and that the concepts of reversibility and retrievability remain important with regard to the effective management of storage and disposal issues. The retrievability of used nuclear fuel from a repository may be required due to repository performance issues and the potential for retrievability can allow for the extraction and reprocessing of used nuclear fuel. It was also noted that new types of waste may be received in repositories that may have an impact on the performance of a repository, or that may require an intervention due to the failure of the waste containers or other barriers.

Reprocessing

Concerning TRISO reprocessing, it was noted that a large amount of research has already been conducted and that 300 000 tonnes of graphite from old reactors remain. Questions were raised on the applicability of recycling technologies for the separation of ^{14}C from bulk graphite and on the potential for breaking TRISO particles.

The panel also discussed and reflected on the following aspects:

- Graphite coming out of TRISO reactors must be considered as well as legacy graphite, and there is room for integration. Lessons can be learnt about graphite impurities that can be applied to TRISO fuel; however, there are differences. New processes being developed for TRISO might be applicable to legacy graphite.
- The reprocessing of TRISO might be possible and options for this are being developed. The extraction of used fuel from graphite is logical from a waste management perspective and also helps to limit the growth of ^{14}C. However, as vendors are motivated to adopt the simplest solution possible, it may be more economical to dispose of graphite than to separate ^{14}C from it.
- Secondary waste coming from reprocessing along with how to deal with this kind of waste (different solvent technologies were mentioned) was discussed and it was noted that many countries have separated plutonium and that fast reactors can use this material as fuel.
- There are different strategies for dealing with waste. With respect to dealing with the risks of security and safety, recycling programmes would need to consider the following elements: the environmental impacts, the removal of hazardous chemicals, the security of the processes that may drive the need for additional barriers, as well as online monitoring and safeguards. An integrated waste management programme considers all of these factors, including the number of waste streams, life cycle analysis, the development of tools to assess the different waste streams and their impact on the final form. For the purpose of disposal, the emphasis is not focused on the removal of plutonium, rather the focus is on trying to keep actinides out of the repository. To that end, the objective of the recycling programme is to reduce the toxicity of the used fuel. As the creation of a new facility is costly, the presence of a facility that extracts plutonium and actinides could be useful.
- Re-enrichment could also be used instead of recovering actinides. Only a few concepts are using high assay fuel, and this fuel must be manufactured, therefore it is not unreasonable to already start reflecting on the impacts this may have on decommissioning. To that end, the selection of materials and the choice of design must be taken into consideration with regard to future decommissioning plans.

The audience emphasised that public acceptability is an important factor; however, the panel discussion had been mainly focused on the economics of reprocessing and to a certain extent on technological feasibility and optimisation. Therefore, the decision-making process may not reflect the societal and technological concerns.

This discussion highlighted the different evaluation processes available to determine the best solution for managing waste.

Repositories

The audience asked whether long-term storage is different from disposal in a repository and what the radionuclide uptake in the environment is from a repository. It was noted by the panel that it is important to understand the objectives of storage. Repository operation is a lengthy process that spans decades and adaptive phase management is a necessary part of the repository programme. Waste disposals last for thousands of years and waste types will change in the future; thus, waste retrievability options should be considered for a long period of time. There are incentives for long-term storage and its benefits must be understood. A good example of this approach is captured under the NWMO's Adaptive Phase Management concept.

The repository's safety case includes analysis of the uptake of radionuclides in the environment from a repository, and ongoing assessments of the environment will always need to be done.

4. Session 3 - Radioactive waste and decommissioning in light water and Generation IV SMR technologies

This session explored whether the current licensing and regulatory requirements are applicable to light water and Generation IV SMRs. It evaluated whether implementers are able to integrate waste generated from light water and Generation IV SMRs into existing disposal strategies and it highlighted the possibility of design and operational optimisation through the incorporation of lessons learnt from the existing reactor fleet in the areas of decommissioning and radioactive waste management. Below is a summary of specific topics presented.

4.1. Licensing and regulatory requirements of spent fuel and waste management for light water and Generation IV SMR technologies

This session explored how regulators have prepared and identified potential regulatory process changes that may need to be considered to properly manage waste and decommissioning activities as a result of future deployment of SMRs. The possibility of regulatory harmonisation was also examined.

Ramzi Jammal (CNSC) introduced this session. He indicated that the full nuclear cycle must be examined, and that the applicant has the responsibility to meet the CNSC objectives. The CNSC does not prescribe specific requirements but provides performance objectives that must be met. For SMRs, the CNSC is aware that there are some unknowns with respect to the radioactive wastes that would be generated, but the acceptability of a proposal must be demonstrated by the safety case.

Waste management from SMRs is a key area of concern for politicians, the public and the Indigenous peoples. Community engagement is paramount, and projects cannot proceed without social acceptability. Vendors must go into communities and communicate with the public.

The CNSC is part of the process, but the industry must not leave the burden for future generations.

Takeaways

- For the licensing of SMRs, the full nuclear cycle must be examined.
- The applicant has the responsibility to meet CNSC performance objectives and the acceptability of a proposal must be demonstrated by its safety case.
- Waste management is a key area of concern for politicians, the public and Indigenous peoples.
- Community engagement is paramount, and projects cannot proceed without social acceptability. Vendors must go into communities and communicate with the public.

Licensing and regulatory requirements of spent fuel and waste management for SMRs/ARTs in Poland

This presentation focused on Poland’s regulatory framework and activities in relation to SMRs. The National Atomic Energy Agency is Poland’s independent regulatory authority, whose role is to ensure that the use of ionising radiation and nuclear energy does not cause a risk to human health and to the environment.

The main tasks of the regulatory body are to: license activities involving use of ionising radiation; conduct inspections to verify nuclear and radiation safety; draft legal acts; issue regulatory guidelines; and monitor radiation in Poland.

The framework is based on the Atomic Law, government regulations and guidelines. The president has no power to issue binding state regulations. The current regulations do not distinguish between large nuclear power plants and SMRs.

Poland has used fuel storage facilities (currently empty), a decommissioned research reactor and an operating research reactor. The objective of the Polish Nuclear Power Programme is construction and commissioning of nuclear power plants with a total installed nuclear capacity of up to 9 GWe based on pressurised water reactors. The first unit is planned to start operation in 2033.

The National Radioactive Waste Repository in Rózan, Poland, is dedicated to the disposal of radioactive waste. It is a surface disposal facility for short-lived low- and intermediate-level radioactive waste (LILW) with a radionuclide half-life of less than 30 years and is also used for storing long-lived waste (mainly alpha-radioactive materials awaiting disposal in a deep geological repository).

The national plan for handling radioactive waste and used nuclear fuel was updated in 2020. A new plan is expected in 2024 and should include policy related to SMRs. The government is working on the development of a new repository for LLRW and ILW and a site selection process for an underground research laboratory and an underground repository. In relation to SMRs, in 2022 two consortia applied for an opinion on the planned organisational and technical solutions for SMRs.

The audience requested an opinion on capacity building and international collaboration. The presenter noted that the regulatory staff are currently 30 with another 35 planned for next year. The organisation receives sufficient financial resources and for the next two years the budget will increase. The regulator is working with international organisations (such as the NRC) to enhance their knowledge in understanding the technology and gain experience on power plant construction. The regulator is committed to oversee the safe construction and operation of a nuclear power plant. As the industry advances in project execution, the regulator will begin harmonising its regulatory framework with the NRC and the CNSC.

Takeaways

- Poland has a national radioactive waste repository, used fuel storage facilities (currently empty), a decommissioned research reactor and an operating research reactor. The government is working on the development of a new repository for LLRW and ILW and a site selection process for an underground research laboratory and an underground repository.

- Poland is looking for the construction and commissioning of new nuclear power plants with a total installed nuclear capacity of up to 9 GWe, with the first unit planned to start operation in 2033.
- In relation to SMRs, two consortia have recently applied for an opinion on the planned organisational and technical solutions for SMRs.
- The national plan for handling radioactive waste and used nuclear fuel was updated in 2020. A new plan is expected in 2024 and should include policy related to SMRs.

Canadian regulatory framework for the management of spent fuel, radioactive waste and decommissioning

This presentation focused on the Canadian regulatory framework. The CNSC is an independent agency of the Government of Canada that reports directly to Parliament through the Minister of Natural Resources.

The CNSC regulates all nuclear facilities and activities in Canada. Federal legislation used to regulate and oversee the nuclear industry, including waste management and decommissioning activities, is comprised of the Nuclear Safety and Control Act, the Nuclear Fuel Waste Act, the Nuclear Liability and Compensation Act and the Nuclear Energy Act. Waste management and decommissioning activities are also subject to the Impact Assessment Act, the Canadian Environmental Protection Act and the Fisheries Act.

The Nuclear Safety and Control Act is the enabling legislation. The Commission makes regulations through a transparent process and regulations are performance-based with safety objectives set in the requirements and regulatory documents. Regulatory requirements are continually updated based on a systematic and transparent process and aligned with IAEA safety standards; adoption of national and international standards and extensive consultation is held with all stakeholders. Regulatory philosophy is risk informed.

The CNSC's regulatory framework for waste management and decommissioning consists of the Act, the enabling regulations, licence conditions, regulatory documents and codes and standards. As set out in REGDOC-2.11, there are six principles that govern the CNSC's regulation of radioactive waste and decommissioning:

- The generation of radioactive waste is minimised.
- The management of radioactive waste is commensurate with its hazard.
- The time frame for the assessment of future impacts encompasses the maximum impact.
- Predicted impacts are no greater than those allowable at the time of the regulatory decision.
- Mitigation measures are developed, funded and implemented as soon as reasonably practicable.
- Transborder effects are not greater than the effects experienced in Canada.

Each stage of a facility's life cycle (siting, construction, operation, decommissioning and release from licensing) requires a CNSC licence. Planning for decommissioning, including waste management and financial guarantees, is required for the first four.

All licensees who manage radioactive waste must:

- Be responsible for its safe management.
- Optimise the steps in radioactive waste management to ensure protection of people and the environment.
- Take into account interdependencies among all steps in radioactive waste management.
- Produce and/or maintain records.
- Develop, document and implement programmes, procedures and instructions.
- Use operational experience, lessons learnt from other similar facilities or activities, and advances in science and technology.

The audience asked if the CNSC could explain the thinking about interim storage for remote communities. The presenter responded that the CNSC will assess any proposal based on its safety case. The CNSC is not for or against interim storage; its decisions are based on the applicant’s safety case. With respect to interim storage for remote communities, this is a matter of government policy. NRCan is responsible for developing and implementing federal nuclear energy policy across the nuclear supply chain, from uranium mining to the final disposition of the waste.

The audience enquired if a financial guarantee for decommissioning would be required for an SMR. The CNSC responded that it adheres to life cycle licensing, and that financial guarantees are required for most phases.

Takeaways

- Canada has a strong regulatory framework for all nuclear activities, including waste management and the decommissioning of nuclear facilities and related activities, and experience in doing so.
- The CNSC is ready to assess licence applications for SMR related activities and in advance is conducting SMR design reviews. SMRs must look at the whole life cycle and designs must include integrated waste management solutions. Long-term waste management must be an integral part of decommissioning planning.

US regulatory perspectives

This presentation focused on recent regulatory preparedness activities, future considerations and decommissioning topics of the NRC. Recent regulatory preparedness activities for advanced reactor fuels include:

- Publication of NUREG-2159, guidance on material control and accounting for special nuclear material of moderate strategic significance (Category II).
- NRC and Oak Ridge seminar on non-LWR HALEU fuel concepts.
- Questions and answers on security for Category II nuclear materials.
- UF6 transportation licensing.
- The NRC also highlighted 12 reports relevant to SMRs.

The advanced reactor fuels roadmap was referred to. It includes:

- Front end (conversion, enrichment, fabrication, fire, criticality and chemical analyses [metal, molten salt]).
- Transportation (UF6, used fuel and fresh fuel criticality analysis, code validation, accident analysis, material characterisation, transportable microreactors).
- Back end (storage including interim, materials characterisation, criticality code validation, chemical/physical form, reprocessing [technical issues, policy issues, international safeguards and material control and accounting]).

In relation to decommissioning in the United States, there are 25 power reactors that are shut down, 17 in active decommissioning and 8 in safe storage. Rulemaking is expected in 2024 for facilities transitioning to decommissioning. In the future, plans to evaluate decommissioning of advanced reactors is expected with specific aspects yet to be determined.

The audience asked what role the NRC/CNSC has in supporting the efforts of countries such as Poland, which is embarking on new build. The presenter noted that the NRC recognises the need for international support and participates in forums like this workshop and the IAEA and also communicates with the CNSC and other regulators. The CNSC responded that it also participates in international committees and forums. As part of the CNSC's funding from the treasury board, funding for international collaboration is included.

Takeaways

- Efforts are needed now to prepare for future challenges.
- Some of the same questions that were looked at 20 years ago are still relevant today.
- The NRCs budget must be developed two years in advance, and thus knowing in advance what is being planned by vendors and operators will allow for the NRC to be responsive to requests.

Licensing and regulation of SMRs/ARs in Korea

This presentation focused on Korea's legislative and regulatory framework. This included used fuel regulation, decommissioning regulation and regulatory experiences in SMRs and advanced reactors. The regulatory research plan was also discussed.

The legal framework includes the Nuclear Safety Act, the enforcement decree, the enforcement regulation, and the administrative regulation in addition to regulatory standards, regulatory guides and safety review and inspection guidelines.

In relation to used fuel regulation, there are 3 operating CANDU reactors and 21 PWRs. Regulation is overseen in all phases of the nuclear life cycle (temporary storage, transport, interim dry storage, recycling and disposal).

In relation to decommissioning regulations, operators are required to submit initial decommissioning plans for their facilities. The criteria for the initial decommissioning plan for SMRs are basically the same for nuclear power plants. The plan must be updated every ten years from the date of the issuance of the operating licence.

For SMRs, the applicants must submit a used fuel management plan from beginning to end as part of the decommissioning plan. There are five SMR designs in Korea with two having marine applications. A standard design approval was given for the SMART reactor in 2012.

Regulatory challenges include new SMR designs, new design concepts, functions and materials and requirements for new legal articles, regulatory guidelines and technical codes. There remains a gap of positions between regulatory authorities and licensees/applicants. The regulatory plan for SMRs/AR is to develop pre-application review documents and design specific review guidelines and safety assessment criteria in the future.

Takeaways

- Korea has a mature nuclear industry and a mature and encompassing regulatory framework.
- There remains a gap of positions between the regulator and licensees/applicants. The regulatory plan for SMRs/ARs is to develop pre-application review documents, specific review guidelines and safety assessment criteria in the future.

SMR waste management in Finland

This presentation focused on the situation in Finland with respect to nuclear power and its application to SMRs. Finland has four operating power reactors and one research reactor. There are three used fuel storage facilities and two low- and intermediate-level waste repositories. Posiva (a private company owned by the nuclear operators) applied for an operating licence for a used fuel disposal facility at the end of 2022 for the Olkiluoto and Loviisa nuclear power plants. There is no national nuclear waste management company, and according to the nuclear energy act and degree the operators are responsible for nuclear waste management.

Currently, there are no SMR projects (one utility operator has started feasibility study for new nuclear power to Finland or Sweden). The current nuclear power plant operators as well as some major utility companies have indicated that they may be interested in building combined heat and power SMRs to replace fossil fuels.

The SMRs under consideration are likely to generate similar waste types to the existing nuclear power plants; therefore, no major issues have been recognised. There is also an assumption that the fuel usage concept is once-through, and there would be no reprocessing. The SMR used fuel is similar to the large nuclear power plants so wet or dry interim used fuel storage would be suitable. There is no need to develop SMR specific safety requirements regarding fuel storage. No SMR specific safety issues have been recognised in the concept, as long as the UO_2 fuel will be disposed of without reprocessing and the enrichment is in similar range as in current reactors.

New operators and new sites are likely to require new LILW repositories. However, since the SMRs might be located in urban areas or at least closer to urban areas to be able to provide district heating, there may be economical reasons for companies to investigate off-site/centralised LILW repositories. This would be a new approach in Finland and will require a full licensing process including acceptance from the municipality where the repository would be located.

The disposal facility is designed and licensed only for the Olkiluoto and Loviisa Nuclear Power Plant used fuel from existing reactors (even if licensing would be changed, the disposal facility has limited capacity). In the case of a new SMR operator, they will need to make an agreement with Posiva and its owners or start the process to construct a new disposal facility. However, there are needs for technical optimisation for SMR fuel assemblies to make it more economical (for example tunnel geometry, capsule dimensions, disposal hole dimensions).

Regulatory work so far has focused on light-water reactors since those are the most mature concepts. Reform of the nuclear energy legislation has been started. The reform process will last for several years. One aim of the reform is to take SMRs into account in the licensing process. According to the current nuclear energy legislation it is forbidden to export or import nuclear waste.

Challenges include:

- The lack of centralised waste management organisation makes it expensive for a small SMR operator to enter the market (this would require a new waste management operator – governmental or privately owned); the issue is not so significant if a new operator has several SMRs utilising the same waste management facility.
- A waste management fund payment is required to be paid in full when the SMR becomes operational.
- The number and nuclide inventory of nuclear waste transports will increase.
- New operators will need more guidance in waste management and safeguards from regulators.

Takeaways

- Finland has a variety of nuclear facilities including nuclear power plants, used fuel facilities and low- and intermediate-level waste repositories.
- Waste facilities are associated with the existing nuclear power plants.
- There is no national nuclear waste management company.
- Operators of nuclear facilities are responsible for nuclear waste management.
- There are some expressions of interest in the development of SMRs, but the lack of a centralised waste management organisation makes it expensive for small SMR operators to enter the market.

4.2. Operational and design optimisation related to decommissioning and radioactive waste management for light water and Generation IV SMR technologies

This session evaluated whether implementers are ready to integrate waste generated by SMRs/ARs into their disposal strategy. Furthermore, it explored whether feedback from current practices in waste management and decommissioning can help optimise the design of SMRs/ARs to minimise the flow of waste and facilitate the efficient decommissioning of future reactors.

Back-end optimisation considerations for advanced fuels/advanced reactors

This presentation focused on considerations for back-end optimisation for advanced reactors including different types of advanced reactors and fuel types. Fuel types discussed were oxide/ceramic fuels with cladding, TRISO fuels, metallic fuels and liquid fuel salts with varying levels of enrichment.

- Oxide/ceramic fuels with cladding – similar in design to an existing light-water reactor oxide fuel pellet (extensive operating, manufacturing, and irradiation experience with uranium oxide and MOX fuel, extensive recycling experience of uranium oxide and some experience with MOX). Additional treatment of used nuclear fuel may be necessary if to be directly disposed of in canisters.
- TRISO fuels – containment of fission products remains in TRISO particles for temperatures up to 1 600°C. No successful recycling efforts demonstrated yet and will have high waste to fuel ratio. Conditioning of fuel to remove/reduce graphite content potentially needed for disposal.
- Metallic fuels – some recycling experience (pyro-processing/electrochemical and aqueous polishing process), conditioning of fuel for removal of internal sodium needed for disposal.
- Liquid fuel salts – liquid fuel allows for online fuelling during operation and real time conditioning/recycling/waste processing (removal of fission products) and leads to significant overall volume reduction, transmutation of actinides and minor actinides in reactor. Conditioning of fuel (polishing and stabilisation) is necessary to avoid fission product buildup in reactors and to produce an acceptable waste form for disposal.

More than 600 possible scenarios exist for back-end fuel cycle management, depending on the specific context and specific choices for a given nuclear system. Key areas of the life cycle approach are interim storage, transportation, treatment, reprocessing/recycling and disposal in a repository. Interim storage and transportation are a critical part of the overall back-end management. Solutions must be available for the various fuel types. Existing solutions like EOS/EAGLE systems, licensed for light-water reactor fuel, can be adapted/modified for such needs.

Treatment and recycling options are described for the various fuel types. Two involve an aqueous polishing cycle, while the others include an electrochemical/pyro-processing recycle and conditioning by removal of graphite. It is noted that a broad range of fuels are already being reprocessed at the La Hague plants.

Takeaways

- Advanced reactors and advanced fuels offer a significant range of scenarios for back-end management.
- Designing the back end of the fuel cycle from the beginning as a system is essential, with a goal to optimise final disposal.
- Sustainability can be achieved by minimisation of waste, preservation of resources, and reuse of valuable materials, with storage and transportation as “key” common activities.
- When possible, a closed fuel cycle offers many advantages.

Comparing legacy waste management to advanced reactor waste management

This presentation focused on the US experience with advanced fuel types. The presentation discussed: fast reactors (sodium-cooled, lead-cooled, gas-cooled and molten salt cooled reactors), molten salt reactors (fluoride or chloride salts as liquid fuels) and high-temperature reactors (graphite moderated thermal reactor and TRISO fuel). It was noted that many fuel concepts are based on past designs or experiments. There are 350 types of fuel being managed by the DOE.

Spent nuclear fuel from advanced reactors is expected to be similar to legacy DOE spent nuclear fuel. Discharged waste forms can primarily be grouped into four categories: oxide, TRISO, metallic and molten salt:

- Oxides from light-water reactors have been stored across the United States for decades (waste management is well established). However, discharged accident-tolerant fuels may require changes in waste management (higher enrichment and burnup, denser fuel).
- TRISO fuels have been transported to and stored in vented dry vaults at the Idaho National Laboratory. For disposal, these fuels were placed in a graphite moderated enclosure. The primary differences in advanced reactor concepts and legacy TRISO includes potential pebbles vs. prismatic block and the level of enrichment (10-20% vs. >20%).
- For metallic fuel management, storage included dry vaults in vented canisters and in small bottles underwater awaiting conditioning. These fuels were transported safely. For disposal, non-sodium bonded metallic fuel may be disposable in DOE standard canisters, but sodium-bonded metallic fuel must be processed to remove the sodium bond. Primary differences in advanced reactor concepts and legacy metallic fuels include additional alloys and enrichment (10-20% vs. >20%).
- For molten salt fuels, residual fuel salt remains stored in fuel drain tanks (in solid state). Transportation and disposal strategies of this legacy waste have not been definitively established. Primary differences in advanced reactor concepts and legacy salts are the volume of salts to be managed.

The DOE has directed funds to analyse the storage, transportation, and disposal of used fuel and high-level waste from advanced reactors. Preliminary considerations include identifying waste streams, damaged fuel, and potential areas for problematic wastes (some waste streams may not neatly fit into a waste category). Storage and transportation guidelines may need to be reconfigured for advanced fuels and microreactors (<20 MWt) may present additional challenges.

Takeaways

- The United States has experience in managing spent nuclear fuel and high-level waste from a broad range of reactors with various waste forms (metallic fast reactors, molten salt and high-temperature reactors).
- The DOE is investing in advanced reactor development and waste management activities associated with characterisation, packaging and regulatory gaps.

SMRs/ARs: What impact on radioactive waste? Principles and analysis methodology proposal

This presentation focused on waste types in power reactors and SMR advanced designs. Waste types are described as used fuel, structural waste from fuel assemblies, internal core components (control rods, reflectors, neutron shielding), decommissioning waste, processing of coolant (sodium), off-gas systems, equipment decontamination and concrete and wastes from routine maintenance and operations.

In the case of high-temperature gas reactors, specific issues for waste include coated fuel particles (e.g. TRISO) dispersed in graphite matrix, helium coolant, graphite moderators and limited experience.

- Positives include absence of waste in the form of metallic claddings, retention properties of the shell, chemically inert helium coolant and a design that in principle is compatible with direct disposal (needs to be studied).
- Negatives include management of graphite (structural elements + moderator + irradiated fuel elements), impact on disposal resources and long-term behaviour during disposal time frames (impact of graphite activation products like ^{14}C).

For particle type reactors, specific issues are associated with the separation of particles and graphite for particle disposal. These include not destroying the cladding layers of the fuel elements, and for processing phase, avoiding carbon residues in order to not impact the extraction process.

In the case of molten salt reactors, specific issues include a liquid fuelled system, various design concepts, a highly corrosive reactor environment and there is no industrial scale experience.

To develop comparable waste assessments between reactor concepts and sizes, many assumptions must be made and clearly explained: why, how many, where, when and what are the specific issues.

This approach must be accompanied by a study of the impact of the SMR concepts on the entire fuel cycle (front and back end including transportation). Proposed criteria will support the assessment of the impact of all SMR waste on waste management in the concerned country and there may be a need to extend existing disposal capacity and/or to develop new capacity.

The audience asked if a methodology had been developed to minimise waste considering lean management principles in order to continuously minimise waste, and if management assessments need to be done country by country? The presenter responded that a methodology does exist, and the assessment will have to be done depending on the country's requirements.

Takeaways

- Depending on the reactor type, all SMR concepts have positive and negative impacts on waste management. All concepts have varying amounts of uncertainty.
- Each country must assess each concept in relation to their existing waste management options, and there may be a need depending on the concept used to extend existing disposal capacity and/or to develop new capacity.

Lessons learnt from decades-long surveillance and maintenance of the molten salt reactor experiment

This presentation focused on the lessons learnt from the molten salt reactor experiment in the United States. In February 2020, the Consortium for Risk Evaluation with Stakeholder Participation was asked to conduct an independent evaluation of human health and environmental risks and potential future impacts of facilities within the DOE cleanup scope at the Oak Ridge reservation.

One of the risk profiles evaluated was for the molten salt reactor experiment. It was one of two molten salt reactors that have ever operated (the other was associated with the defence programme and was operated on an airplane). It is presently being held in a surveillance and maintenance state.

The reactor ceased operation in 1969; however, the fuel salt is still stored in the drain tanks below the reactor, which has presented chemical and radiological hazards over the more than 50 years since it operated. The expected date for removal of the salt from the drain tanks is 2056 (almost 100 years after reactor operations ceased).

Fuel salt constituents are subject to gamma-induced radiolysis from fission products in the salt. Subsequent reactions involving unstable free fluorine can result in the production of fluorine gas and uranium hexafluoride.

For almost 20 years after reactor shutdown, the fuel salt was annealed (i.e. heated to below melting temperature) annually to cause fluorine to recombine in an attempt to prevent its migration from the drain tanks. In 1994, high concentrations of fluorine and uranium hexafluoride were found in the off-gas system and a significant deposit of uranium was found in the auxiliary charcoal bed (in excess of three minimum critical masses).

Over the next 5 years, contractors and the DOE developed and executed a plan to remove approximately 80% of the uranium deposits from the charcoal bed cell. After elimination of the criticality concern from the charcoal bed, efforts were directed towards avoiding a similar occurrence in the future.

Although defueling has been completed, the fission products within the drain tank still result in radiolysis-induced gas generation in the headspace of the drain tanks. To prevent over-pressurisation of the headspace, and to reduce the inventory available for potential release, a ventilation system (modified from operations) is used to twice per year pump down gases in the headspace.

Under this treatment scheme, the potential gas exposure hazards to facility workers dominate the facility’s risk profile. A continuous purge system is now being implemented to replace periodic pump down with the ventilation system to reduce risks to workers.

Takeaways

This case study highlights some important questions for SMR/AR designers, such as:

- Is the reactor design prepared to withstand (significant) delays in deactivation, decommissioning or demolition due to potential regulatory, budgetary or technical unknowns?

- How could the risk/hazard profile of the reactor design change during the retirement process (i.e. are there phenomena that require additional study now to prevent issues later)?
- Does the reactor design include preventative/mitigative features to reduce risk to workers and the public given unexpected delays? Are operational systems sufficient to reduce risk during unexpected delays?
- Are there potential delays in deactivation, decommissioning or demolition due to supply chain or critical services procurement issues that could be anticipated now?

Roundtable discussion on waste implications from the deployment of SMRs/AR technologies

The roundtable consisted of the previous presenters and other invited guests and began with comments from the audience. General topics included reactor design, decommissioning and chemical wastes.

Reactor design

The audience noted that a recent paper reviewed different reactor designs, each of which have different advantages and disadvantages and inquired which type would be the most successful. While no single factor may drive the decision, it may be a combination of factors. In the United States, safety should not be an issue with all the reactor types being proposed, and the best reactor design would be the one that provides the most profit. Times have changed and large capacity reactor types may no longer be the driving requirement. There are other drivers for SMRs, rather than their use in replacing existing power reactors as the need has changed and high-temperature reactors have now come to the forefront.

In relation to the adaptability of reactor design, it was noted that in the past, naval operations drove design and R&D that focused on that specific application. At the time, those designs were seen as best practice and were adapted by some commercial reactor designs. Since then, lessons learnt have been considered in the development of new designs. Moving forward, there needs to be continuous adaptability in design, inclusive of all aspects of the fuel cycle.

The audience asked what message should be sent to the public on the technological readiness of SMRs and that perhaps light-water reactors must be kept. The panel responded that part of the issue with a big facility is economics, as they cost so much. There might be other challenges. There are segments of the population that believe that greenhouse gases are a threat to their future, and this drives their opinions, while other segments of the nuclear industry are emerging that demand a solution to the high cost of light-water reactors.

Decommissioning

The audience observed that the panel seemed to be critical of older reactor designs. The panel responded that the issue is the percentage of decommissioning costs that are required. In general, decommissioning costs should be low compared to other life cycle costs, but with older reactor designs it seems that the activity of decommissioning is more difficult, and hence more expensive. With this in mind, there is an opportunity now to create a link between the reactor designers and those that will decommission the reactor.

The facilities built in the past did not incorporate much thought of decommissioning in their design principles and this has caused difficulties in conducting decommissioning today. Moreover, actual decommissioning costs of reactors are higher than are usually forecasted. Old research reactors had smaller capacities while new designs have higher capacities and are more conducive for decommissioning. Nuclear power plant construction was guided by building structures around the reactor rather than guided by the need for future disassembly. The proprietary nature of the reactor designs could have hindered the free exchange of ideas in relation to future decommissioning. However, during licensing, proprietary information may need to be shared.

With respect to decommissioning costs, power plant construction requires high capital costs followed by decommissioning costs, especially for legacy facilities. The timing of decisions and investments is also important since the impact of inflation also needs to be considered.

From a social perspective, communities require that decommissioning be conducted now and not decades in the future. New decommissioning projects seem to be doing well but legacy facilities that are in safe storage are not. Decontamination and cleanup requirements were mostly politically driven during the cold war. In the 1990s, billions of dollars were spent building new facilities that will need to be decommissioned.

Chemical wastes

The audience inquired about the chemical aspects of wastes in repositories from SMRs. There are robust R&D programmes that looks at these factors. This information must be presented in the safety case, including chemical effects.

4.3. Operational feedback on management and disposal of existing waste streams and how some of these concepts can be applied to future endeavours, such as light water and Generation IV SMRs

This session highlighted lessons learnt from radioactive waste disposal projects as well as dismantling and decommissioning activities. The aim was to share information with designers and utilities to minimise overall radioactive waste volumes expected from SMRs, and to manage fuel damaged during operation. It began with a presentation from the NEA.

The NEA's overview on lessons learnt from current reactor decommissioning and radioactive waste management activities

This presentation focused on lessons learnt from current reactor decommissioning and radioactive waste management activities. The NEA's framework for managing the back end is comprised of two committees: the Radioactive Waste Management Committee (RMWC) and the Committee on Decommissioning of Nuclear Installations and Legacy Management (CDLM). Themes that these committees look at include environmental factors, societal factors, regulatory/legal aspects, operational safety, economic factors and knowledge management. Key challenges identified in the back end of the nuclear cycle include insufficient pre-planning, lack of optimisation and ineffective communications.

Insufficient pre-planning includes factors such as core components being left in temporary storage, embedded underground piping that leaks, undefined disposal routes (unconventional waste such as graphite, reactive metals, pyrochemical waste and beryllium) and lack of a radioactive waste management life cycle.

Lack of optimisation includes non-adequate funding for waste management and decommissioning, competency of maintenance, knowledge transfer and information management, the stability of solutions/decisions for the long term and lack of appropriate hazard and risk assessments.

Insufficient stakeholder engagement includes decision-making processes' lack of collaboration/integrated approach, conflicting national and international regulatory standards and that all stakeholders are not sufficiently engaged throughout the fuel cycle process.

Lessons that have been learnt from decommissioning include that optimising the design for decommissioning saves time, money and dose; improving response timeliness to incidents pays dividends in the future, improved evaluation of materials, processes and decommissioning funding requirements; and the need for overall optimisation of all factors in all steps and engaging all stakeholders throughout the fuel cycle process.

Lessons learnt from waste management includes the need to implement a waste hierarchy, encourage timely characterisation and segregation of wastes, enable risk-informed waste management with an emphasis on the nature of the waste rather than the waste classification, in order to identify the most appropriate waste management approach. Another lesson learnt included the importance of developing a single waste management strategy to optimise the management of the waste based upon its risk and to ensure waste management infrastructure is flexible to facilitate prompt decommissioning and remediation of facilities.

The audience asked if there is a restricted network or database where all the information is captured. The presenter responded that all reports are publicly available through the NEA website. A network/database that houses non-public information does not exist.

Takeaways

- Challenges from the past will be found in the future if no corrective steps are taken.
- New designs are unique opportunities to address lessons learnt to support sustainability in nuclear energy.
- Designers should engage early with all stakeholders.
- The NEA is ready to support international co-operation to address these issues.

Managing challenging waste and lessons for advanced reactors – a UK perspective

This presentation focused on waste issues in the United Kingdom. It was noted that the UK inventory consists of over 6 700tU of legacy oxide, metallic fuel, and a wide range of R&D fuels which have relatively small volumes and unique disposal solutions. Legacy SF will occupy a packaged volume of around 17 000 m^3 in the UK Geological Disposal Facility (GDF). There are also challenging reactor and fuel cycle intermediate-level wastes to be managed.

The United Kingdom is pursuing development of a geological disposal facility as well as pursuing the development of new reactors, with UK ambitions increasing from 16 GW of light-water new build to 24 GW of new build, and potentially including both SMRs and AMRs. A UK geological disposal facility is required to accommodate the complex inventory from a legacy of research, defence, power generation and fuel cycle wastes. Challenges of the existing inventory include managing heat, chemical reactivity and gas, post closure criticality, and demonstrating long term post closure safety. The inventory already represents a challenge in terms of the level of complexity associated with managing a wide range of waste package designs and range of fuels. Ideally a GDF programme would look for as much standardisation as possible. The types of waste streams include:

- Reactive Metals. Reactive metals are an unavoidable feature of much of the United Kingdom's radioactive legacy including uranium, Magnox fuel cladding and aluminium which all pose hazards to disposability due to their reactions with water resulting in expansive corrosion products, hydrogen gas and heat. These have the potential to affect the stability of the disposal systems; compromising the integrity of waste packages and challenging the ability of the waste form and its containers, other parts of the multi-barrier system to fulfil their safety functions.
- Graphite. The British nuclear industry invested heavily in graphite reactor technology, with every advanced gas-cooled reactor and Magnox reactor having a graphite core. Several fuel designs also incorporate graphite structural components. The enduring ^{14}C challenge from activated nitrogen in graphite currently precludes disposal of much of the graphite in existing UK low-level waste routes. The total UK legacy graphite inventory, currently assumed for disposal to GDF, is 70 000 tonnes, arising from UK research reactors and a total of 40 Magnox and AGR gas-cooled reactors (UK Government, 2019).
- R&D, high enriched, unirradiated and MOX fuel. The UK Inventory includes everything from MOX pellets to unused fuel assemblies and high enrichment fuels. Significant and enduring criticality challenges requiring changes to how post closure criticality risk is assessed.

Challenges from advanced reactors include:

- Operating models - potential changes to time of arising, and planned duration of pre-disposal cooling for spent fuel and novel fuel design. This could present both temperature management and disposal system complexity challenges.
- High burnup and the potential for higher enrichment fuels – temperature and post closure criticality management challenge.
- Unused fuels - Shortage of data to demonstrate long-term evolution. Shortage of data to validate criticality safety models at applicable enrichments.
- Novel waste forms - molten salt reactor fuel and coolant, metal cooled fast reactors and accident-tolerant fuels all involve unique wastes with little or no data regarding their long-term performance.

The audience noted that there are 50 years of radioactive wastes being stored at Sellafield and asked if someone should look at how it has evolved. The presenter responded that, yes, there is a significant amount of research on legacy problems, including the evolution of the waste.

The audience asked what happens when there are chemical and radioactive wastes together and how they are considered. The presenter acknowledged the existence of toxic waste that is a health hazard and must therefore be managed in a way to account for that.

Takeaways

- Design for waste-informed decommissioning is vital. Now is the time to consider the full life cycle.
- Some designs under consideration can draw on disposal R&D experiences but even these could challenge existing programme assumptions. Early engagement is needed.
- In the UK, there is a wide range of legacy used fuel and waste to manage and although there is good data, unique solutions may not be suitable for large scale disposal.
- A wider range of designs brings disposal system complexity and complexity costs. Innovation must be supported but it should be balanced with the need for standardisation.
- Some technologies will challenge design and safety conservatisms.
- There is limited experience with disposal of some fuels and waste forms yet decisions on investment in technology appear imminent. Investment on supporting R&D is needed.
- Mistakes must be learnt from the past.

Waste management strategy in France – operational feedback

This presentation focused on waste management strategy in France. In this presentation, waste categories are described as very short-lived waste ($T_{1/2}$ < 100 days), short-lived waste ($T_{1/2}$ <= 31 years) and long-lived waste ($T_{1/2}$ > 31 years). France has developed repository solutions for these types of wastes.

The CIRES facility was developed for very low-level wastes. Its concept is a near surface disposal mound with appropriate watertight liners. It has been in operation since 2003 and has a total capacity of 65 000 m^3 of which 63% was used by 2020. One cell within the facility is devoted to heavier waste types containing a 130-tonne overhead crane for unloading.

The Aube facility is a disposal facility for low- and intermediate-level short-lived waste comprising of near surface disposal vaults with a multi-layered barrier system. It is considered a nuclear installation and has been in operation since 1992. It has a capacity of 1 000 000 m^3 and is currently 35% full. Its wastes are mainly related to materials from maintenance and dismantling of nuclear facilities.

There are also two projects in development:

- The low-level long-lived waste project is a shallow disposal area for low-level long-lived waste that is currently in the conceptual stage. The main issues include the diversity of the waste in this category, safety issues associated with the long life of the waste, and environmental issues (strong requirements for preserving biodiversity and soil artificialisation).

- The Cigéo project is a deep geological disposal concept for high-level and intermediate-level long-lived waste to be developed in France. The concept is designed to be reversible for at least 100 years.

The audience asked about future SMR wastes when they become available. The presenter responded that these facilities have a long life cycle and should be able to accommodate a variety of waste types.

Takeaways

- France has both a low- and an intermediate-level waste disposal site currently in operation.
- It is developing two other projects, a deep geological repository for high-level wastes and a low-level long-lived waste site.

Considerations for the management of spent nuclear fuel from advanced reactors

This presentation focused on spent nuclear fuel in the United States from advanced reactor types as there is growing interest in advanced reactors with a range of fuel designs under development. The presentation began with referencing points extracted from the 1957 National Academy of Sciences committee on waste disposal. They included:

- Repository Construction Timeframes - “We stress that the necessary geologic investigation of any proposed site must be completed before authorisation for construction is given. Unfortunately, such an investigation might take several years and cause embarrassing delays in the issuing of permits for construction”.
- Repository Siting – “We consider disposal in permeable beds should not be done below the water tables, unless subsequent information indicates that adsorption will protect the aquifer above. This method of disposal is worth investigating but cannot be recommended at the present time. Extensive research will be needed, with no guarantee of success”.
- Waste Treatment - “But for the immediate future, extending to many years, wastes will constitute a serious problem. It is an encouraging possibility that in the future people can produce wastes that can be gotten rid of more easily”.
- Public Relations and Acceptance - “Obviously, if the [nuclear] industry is to grow in a healthy way, it must be a “good neighbour” … having harmonious relations with the rest of the community”.
- Transportation - “Some citizens object to having radioactive waste hauled across their water supply”.

Considerations that were identified include regulatory framework, total inventory volume, characteristics, public engagement (and acceptance) and repository location and geology.

The regulatory framework must be assessed for advanced reactor waste forms. Agencies include the Nuclear Regulatory Commission, the Department of Transportation, Customs and Border Protection, the Transportation Security Administration, the US Coast Guard, the Federal Railroad Administration, the Department of Homeland Security, the Federal Motor Carrier Safety Administration, the Pipeline and Hazardous Material Safety Administration, and the Federal Aviation Administration.

Characteristics impacting transport, storage and disposal need to be understood and in line with regulations (radiological, physical/chemical properties).

In relation to public engagement and acceptance:

- Opposition to waste management siting is still a concern. The increase in nuclear energy support has not translated into greater acceptance for accepting waste management facilities.
- Many communities still oppose hosting a waste management facility for storage and or disposal.
- There is a lack of trust in industry, government, etc.
- Opposition and lack of trust lead to "Not in my backyard (NIMBY)" movements.
- How consent is defined and secured must be established.
- Many states have restrictions on construction of new nuclear power plants and facilities for storage and disposal.

The audience noted that the 1957 report was extraordinary and asked what has changed, why there hasn't been more progress, and whether there will be more confidence in waste management in the future. The presenter responded that the same conversation is still being had today, such as how waste is transported and how it is stored. Waste forms can be managed, but there needs to be more collaboration with the public.

The audience noted that the 1957 report referred to putting waste in the ground immediately. There was no talk about repositories and the issue of liquid waste was mostly considered. The report did not consider the use of boreholes. The National Academy of Sciences report can be accessed through the academy's website.

Takeaways

- The regulatory framework needs to be considered for transport, storage and disposal.
- The repository's location and geology are important.
- It takes time, effort and a lot of research to consider waste management options.
- The characteristics of waste are important to understand for transportation, storage and disposal.
- Total volume required is uncertain, but estimates are needed, which is a challenge because it is not known which advanced reactor is going to be commercially successful.
- Public engagement and acceptance must be sought from the first day.

Canada's repatriation programme: Lessons learnt from the transportation campaign

This presentation focused on lessons learnt from Canada's repatriation of highly enriched uranium to the United States. Canada has no disposal option for this type of fuel. At nuclear security summits it was decided:

- to repatriate all eligible US-originated fuel stored at Chalk River Laboratories;

- to expand co-operation with the United States to include target residue material and G1 booster rods;
- to reaffirm commitments to the existing repatriation programme;
- to discuss repatriation of plutonium.

Materials repatriated to the United States included:

- Poot Test Reactor and SLOWPOKE reactor (shipped in 2010, 9 fuel assemblies);
- SLOWPOKE reactor cores (2 shipped 2012, 611 fuel elements);
- NRU/NRX fuel rods (1 000 fuel assemblies, 55 shipments from 2015 – 2019);
- target residue materials (23 000 L – uranyl nitrate, 115 shipments, 2017 – 2020);
- other materials (16 Total Shipments, 2013 to 2022).

This was accomplished by building relationships, building confidence, gaining experience, ensuring security and understanding the challenges:

- Building relationships: Discussions with the CNSC and with US counterparts started in 2013.
- Building confidence: Portable demonstrations for relevant authorities were implemented, including several liaison visits to both border crossings.
- Gaining experience: Capability and endurance were built, and capacity, knowledge and expertise were developed.
- Ensuring security: Two routes, multiple in-person workshops, code word campaigns, and a fixed calendar with multiple alternative shipping dates were established, as well as the use of an electronic tracking system and an overall transportation security plan with a review 72 hours before each shipment with relevant authorities.
- Understanding challenges: These included having one provincial, one international and seven US state borders, one weapons state and one NPT signatory, different security requirements at each border, and Commercial Vehicle Safety Alliance level 6 inspections. The transport of uranyl nitrate liquid had never been conducted before.

The transportation campaign resulted in 189 total shipments between 2013-2022 totalling ~575 kg of highly enriched uranium. Two minor incidents occurred (not accidents).

Takeaways

- The successful completion of repatriation activities of highly enriched uranium to the United States from Canada was accomplished by building relationships, building confidence, gaining experience, ensuring security and understanding the challenges.

Applicability of current Finnish disposal methods for spent fuel from small modular nuclear reactors

This presentation focused on the applicability of current Finnish disposal methods for used fuel from SMRs. Small modular nuclear reactors are being considered as part of the solution to producing clean, stable and secure energy. The replacement of fossil fuel-based district heating systems is especially interesting for Finland. Safe and efficient management of nuclear waste is a prerequisite for deployment of SMRs. A small national research project began in 2021 with the aim of beginning to:

- study the differences between used fuel and other waste produced in SMRs in comparison to the waste produced in a large nuclear power plant;
- assess the applicability of the current waste management methods in use;
- develop SMR waste management strategies and identify regulatory framework challenges and opportunities.

This work continued in 2022 in co-operation with the Geological Survey of Finland in a follow-up project called “SMR Siting and Waste Management”.

The ONKALO used fuel repository is in Olkiluoto, Eurajoki (West-Finland). The development of the concept (originally developed by SKB, later in co-operation with Posiva Oy) and the site selection process began in the late 1970s. The repository depth is 400-430 m with an access tunnel length of 10 km. An encapsulation plant is currently being constructed at the ground surface. The engineered barrier system in a KBS-3V repository includes components such as a fuel canister, bentonite-based buffer and backfill and closure materials. There may be some limitations in using similar type of barriers for SMR wastes as heat generation from the spent fuel canister surface should be limited to 100 C to ensure mineralogical stability of the clays used.

It takes a significant amount of time to develop and construct a repository, and site-specific conditions are crucial for the safety case.

Conclusions were made about used nuclear fuel characteristics as follows:

- The lower discharge burnups in SMRs lead to lower decay heat and ionising radiation at the assembly level.
- Concentrations of mobile nuclides in SMR used fuels are lower.
- The lower average burnups in combination with high enrichment variations may contribute to higher post-irradiation reactivities.
- Considering similar discharge burnups, the model provides used nuclear fuel inventories that are similar to European pressurised water reactor fuel.
- Additional nuclear fuel characteristics are being studied.

Applicability of current management methods:

- European pressurised water reactor fuel assemblies should be compatible with current encapsulation methods using shorter canisters.
- Differences in fuel dimensions, configuration, fission product inventory, decay heat generation, physical and chemical characteristics and fissionable material content would need to be considered in repository design (used fuel mass per canister, canister spacing, etc.).
- The KBS-3V disposal concept (used nuclear fuel is encapsulated in copper canisters that are deposited in vertical deposition holes in crystalline rock) was designed for uranium oxide fuel with specific properties; the disposability of fully characterised SMR used fuel will need to be demonstrated.

Some studies suggest that SMR use may lead to more used fuel and low- and intermediate-level waste being generated per GWe-year than in large nuclear power plants, but these results need to be verified (the actual waste amount might not be the only metric as there is the radiotoxicity / heat generation aspects that may be less in low discharge burnup fuel even if the disposed mass is more). The audience noted that results from fuel need to be verified. The presenter responded that all results have to be verified further.

The audience asked what guidance would be given in relation to SMR models. If the SMR plants are geographically distributed, transporting spent fuel to a centralised facility for disposal can be a challenge. For example, considering cooling times before transport, ensuring safe transportation routes, and ensuring security of storage and transport will also need to be considered and planned for.

The audience commented that in many respects the technical challenges are similar. What has changed is engagement with the wider community since waste disposal strategy from light-water reactors has not been implemented in many countries. The theme is that trust is the main issue. For instance, there is less trust now from the public than in the past and that is a big change. People are demanding more information. The presenter responded that the industry is learning in dealing with the public and with light-water reactors the public has been engaged. The industry must be open and transparent, and a lot of progress has been made since 1957, but there is still more to do.

Takeaways

- The KBS-3V disposal concept is thought to be generally applicable for used fuel management from light-water reactor SMRs. Disposability and effects on the disposal concept and design will need to be assessed when actual irradiated fuel data is available.
- Used fuel characteristics, chosen disposal concept and site characteristics are key factors in the final disposal of used fuel from SMRs.

4.4. Panel discussion on key takeaways and recommendations

The key takeaways/recommendations from this session were discussed by panel and the presenters, and the audience was given the opportunity to ask questions. The discussion was diverse in nature and covered a variety of topics including standardised fuel canisters, safeguards, economics, emergency response, enriched uranium transport and repositories.

Standardised fuel canisters

The question was raised as to whether there is an interest in having a standardised fuel canister and fuel design. In the United States, there are 100 fuel types and although the DOE considered the use of a standard container for storage, transport and disposal, it never came to fruition. One of the challenges associated with the use of standardised canisters is the lack of a defined repository site. For example, salt has better characteristics for a repository, but if there is a different rock type, a different container is needed. To that end, the canister design was standardised as much as it could be.

In the United Kingdom, there are a range of fuels and designs and there are lessons which can be learnt from other industries in terms of reducing system complexity through to disposal. Designs can be standardised up to a certain point, but specific elements within the design must be customised for the properties of the payload and this is one of the challenges with the design development process. The United Kingdom is drawing lessons from other disposal programmes, such as the Finnish repository.

Safeguards

The question regarding the regulation of safeguards and accountancy was raised by the audience. The panel stated that this topic area is rather difficult to fully answer. Many safeguard activities are related to international treaties, which is a delicate subject area. The NRC has a well-connected network that is mostly focused on commercial use. No country enters the nuclear field without considering non-proliferation considerations. Operators need to seek out how their site's impact proliferation, and they need to be well-versed regarding all the applicable rules and regulations. Canada will never approve of the transportation of materials to other countries that are not signatories to a non-proliferation agreement.

The IAEA has been considering plans for repositories in relation to safeguards issues. Safety, security and safeguards is a topic that has yet to be discussed for repositories. Questions such as who should be regulating the security of a closed repository need to be properly addressed. The IAEA is strongly advocating for safeguard assurances and for the monitoring of repositories. For example, countries such as Poland already have requirements in place for security measures and associated monitoring plans for repositors.

Economics

The audience noted that even though countries such as France are adequately addressing the back-end matters, economically-speaking, the nuclear industry is not on a level playing field in relation to other industries as other industries and competitors are not required to consider the effect of carbon that they are emitting.

With respect to recycling, the panel stated that national policies will influence the adoption of recycling options. In the United States for example, the national policy states that there will be a deep geological disposal facility and that the government must take responsibility to dispose spent fuel in the repository. In Canada, it is the responsibility of the operator to manage the disposal of spent fuel and the operator needs to have a financial guarantee in order to be issued with a licence.

Emergency response

The audience inquired about the emergency response plans during the transportation phase. Canada has an emergency response centre open 24 hours per day for accidents or incidents on-site. Different scenarios concerning the transportation process must be reviewed with the police three years in advance due to the regulatory licensing process. The regulators require that a security and response plan must be provided before a licence can be issued for these activities. This is the same in the United States, where applicants seeking a licence must develop and analyse a response plan, which in turn will be reviewed and approved by the regulator. Emergency responders have contact with different states and territories. All parties that are part of the emergency response plan have obligations.

The audience asked about the economic feasibility of district heating and sought clarity on whether a facility needs to be close to population centres/populated areas. Additionally, the audience was keen to know how public concerns would be addressed.

The audience was informed that this is a complex issue and that it will be a challenge to deal with the stakeholders. The point was further raised that emergency preparedness is needed. To alleviate some of the stakeholders' concerns, facilities can be built underground to be more flexible, but the panel noted that more studies would be needed for this approach.

Enriched uranium transport

The audience sought the panel's reflections concerning communications with First Nations in relation to the transportation of highly enriched uranium and whether there are any provisions in Canadian laws that require that Indigenous peoples must be informed about the details of this transportation process. The panel stated that First Nations are informed whenever a transportation process is planned. However, since it is a Category II shipment (i.e. detailed plans cannot be shared for security reasons), it is only a general presentation with no specific detail.

Due to security concerns, detailed information regarding the transportation process is only provided to the regulators with top-secret clearance and this information is only shared with regulatory staff that are involved in this activity and need to know this information. This process is also applicable for operators as under the licensing terms, the operator must have a public information programme and the public must be informed of the activity. It must be noted that there is a delicate balance between providing general information and detailed information regarding the transportation process.

Repositories

The problem of waste optimisation and management options in relation to repositories are a country-specific issue. Countries are conducting research regarding the performance of rock in repositories. The Finnish authority has made some progress in this area, and this could serve as a key learning point for other countries. Sweden is not far behind.

5. Session 4 - Key considerations for communities, Indigenous peoples and stakeholder involvement

This session explored the views of Indigenous peoples and other stakeholders on good practices for stakeholder engagement, highlighting factors to consider to enhance trust and confidence building in the engagement process. A summary of the presentations made in each subsection is presented below.

5.1. Indigenous community/tribal nation perspectives on the potential deployment of light water and Generation IV SMRs

In this session, the Chair introduced the presenters, their educational background, their accomplishments, and their connection to their communities. This included their unique cultural perspectives on the Indigenous culture, the importance of community elders, their ancestors, and their tradition of maintaining Indigenous knowledge through learning from their elders and knowledge keepers.

Reconciliation: Leaning into the richness of Indigenous knowledge systems

This presentation described the activities of the Turtle Island Institute, whose aim is to work on systems change, reconnecting with the land, individual relationships rather than colonial approaches, developing holistic approaches to learning together and spiritual integrity, learning from elders and knowledge keepers, and developing an ethical framework within Indigenous lands.

The presenter spoke of dealing with data and what data looks like – it could include a song, a dance and walking on the land. The ways of Indigenous peoples in developing relationships, and how wisdom can be gained through elders were described. Important values such as bravery, courage and humility are important to the Indigenous communities.

In relation to providing communities with technical project information, the presenter noted that sharing a technical report would likely be quickly forgotten, but other things like sharing values, a song or a painting have more relevance to Indigenous values.

Indigenous peoples have developed technology in their own ways. For example, canoes and other structures were created by Indigenous peoples and have allowed the peoples to develop trade routes to grow and expand their economies.

While the western world is creating plans and seeking the consent of Indigenous peoples, it is important to note that appropriate preparation must be made when working with Indigenous communities. That means developing relationships with communities, having knowledge of the past and implementing reconciliation.

It is important to know that discussions with Indigenous communities may not be comfortable at times, but they are important. To develop meaningful relationships with these communities, Western culture may have to learn to have these uncomfortable discussions.

Takeaways

- In relation to providing communities with technical project information, sharing a technical report would likely be quickly forgotten, but other things like sharing values, a song or a painting have more relevance to Indigenous values.
- Appropriate preparation must be made when working with Indigenous communities. That means developing relationships with communities, having knowledge of the past and implementing reconciliation.

Curve Lake First Nation

The session Chair (retired chief of Curve Lake First Nation) provided a presentation focused on Indigenous perspectives on the history of colonisation and its impact on the Indigenous way of life.

The Curve Lake First Nation and the services it provides to its peoples were described. These include a school to grade 3, a health centre, a health support centre, a cultural centre and an ageing water treatment system. It is the largest community in Ontario with about 2 000 people on-site and spread across the globe.

The economic challenges of the community were described. Funding for the community is provided from the federal and provincial governments but there is no tax base to provide additional funding. Funding received is compartmentalised and can only be spent on the federal government's priorities. For example, funding for education cannot be used for other community needs such as water treatment. Funding that is not used must be returned to the government and cannot be carried over or changed to cover the cost of a different project.

The presenter noted that there is never enough funding and that, for example, teachers are underpaid in relation to non-Indigenous communities. The lack of clean drinking water is an issue for the community as it is difficult to maintain the operability of a 37-year-old water treatment plant with no funding. Consequently, communities are always looking for more opportunities to increase funding. The treaty that was signed was discussed and it required resources to be shared. The only mechanism for that today is through federal government transfer payments.

The Indigenous community has experienced a broad and uncomfortable history. The presenter referred to the legacy of the residential school system (government-sponsored religious schools that were established to assimilate Indigenous children into Canadian culture). This practice had tragic consequences for Indigenous communities, their children, and their way of life. The presenter also spoke about the missing and murdered Indigenous girls and women in Canada (a human rights crisis that has only recently become a topic of discussion within the nation, referring to the thousands of Indigenous women and girls who have been subject to disproportionate violence in Canada). The presenter noted that there must be awareness that these things happened, and that it is not past history but contemporary history (the last residential school closed in 1996). It is a part of the Indigenous peoples' past, and it must be part of the conversation as relationships with Indigenous communities are being developed.

The presenter noted that the government has had conversations about green energy (wind and solar), but it is not a large part of the energy mix and nuclear is required to meet energy needs. The presenter noted that Indigenous peoples' relationship with nature is based on the view that people are not the central focus of the world. Plants, animals, and the land are just as important as people are; one is not above the other and everything is interrelated and interconnected. The Indigenous view is that people only take from nature what is needed to survive. Consequently, Indigenous prayers are not necessarily only religious prayers, they are prayers about being grateful and thankful for things that are provided, for family, for learning about life cycles and for the time that is given.

Conversations about nuclear energy need to include the full life cycle, an uncomfortable and difficult topic for the industry. Everything has consequences, and energy development has consequences, even green energy. This is true, for example, of the environmental effect of lithium mining on the environment, and the end state of wind turbines. That conversation needs to be held.

To learn about used fuel, the presenter visited Ontario Power Generation. But Indigenous peoples need other honest conversations about the end-of-life cycle for the development of all energy approaches. All energy production has consequences, and they need to be understood before honest conversations about nuclear energy and SMRs can be held.

First Nations have moved to a point where jobs are being offered in energy sectors. There are now conversations that are much more meaningful to First Nation communities such as equity ownership in energy projects. Enbridge has provided an incredible opportunity for many First Nations. With that, First Nations are very interested in equity ownership of nuclear power. This is about the sharing of resources that the treaties were based on. These conversations need to move forward as well as equity ownership of resources. Opportunities for young people need to be created and the importance of youth and education needs to be recognised.

Takeaways

- The Indigenous community has experienced a broad and uncomfortable history, including the legacy of the residential school system and the legacy of missing and murdered Indigenous girls and women. It is a part of the Indigenous peoples' past, and it must be part of the conversation as relationships with Indigenous communities are developed.
- Indigenous communities can have economic challenges, so communities are always looking for more opportunities to increase funding.
- Conversations about nuclear energy need to include the full life cycle. Indigenous beliefs include the notion that everything has consequences, and that all energy development has consequences. This needs to be well understood.
- Treaties with Indigenous peoples have been based on the sharing of resources. First Nations are very interested in equity ownership of nuclear power and conversations on this topic need to move forward.

Site-specific tribal engagement on SMRs

The presenter provided an overview of the activities of the Shoshone-Bannock tribes of the Fort Hall Reservation and their interactions with the DOE in southeast Idaho.

As part of the Fort Bridger treaty, lands were set aside for the permanent home of these tribes, which allowed the making of a permanent reservation and the use of unoccupied lands for hunting and gathering. The reservation currently exists across 544 acres, down from 1.4 million acres previously due to encroachment and settlement.

Due to the development of the Idaho National Laboratories, many shipments including used nuclear fuel have to travel through tribal lands. With the development of the laboratories, the tribes were still able to use the ancestral lands. But before 1992 there was no agreement that allowed the transport of nuclear materials.

The DOE was not upholding federal trust responsibilities to the tribes as there should have been consultative discussions and agreements. This resulted in the Shoshone-Bannock tribes blocking the rail shipments of used nuclear fuel to the facility. This precipitated further discussions with the DOE and an agreement was reached that DOE activities are protective and preventative of tribal interests in ceded territories, Aboriginal lands and treaty lands.

Now, tribal staff do environmental monitoring, emergency response and cultural resources protection. A two-tier system of consultation has been developed, leadership to leadership, and staff to staff. Any potential federal actions on federal lands require this consultation.

Six SMR designs are currently being looked at. This has been ongoing since 2016 when the tribes first got involved. Consultations continue between the tribes and the DOE, the facility owner, the reactor designer and the NRC. Some issues have been identified, such as the fact that the site area is considered sacred and access to the sites may be impacted.

Takeaways

- A government-to-government relationship is fundamental for success in maintaining relationships with tribes. The federal government has trust responsibilities and must consult with the tribes on federal matters that may impact them. But there is uncertainty in defining private-tribal engagement.
- Tribal engagement on projects can impact tribal interests. There is a lack of resources (staff, funding and expertise) and there are concerns over environmental safety and emergency response. Cultural and historical knowledge is important for protecting and preserving tribal culture and for protecting access to sacred sites.

Creating space for meaningful engagement with Indigenous communities

This presentation reflected an overview of the presenters' work with the NWMO and in engaging with Indigenous communities.

This work began in 2002 with the formation of an advisory council that included Indigenous representation. Dialogue with Indigenous communities continued and in 2005 an Elders Forum was formed, which is now called the Council of Elders. The presenter joined the forum in 2009 as an independent advisor.

In 2014, the importance of youth was recognised as they will be involved in the impact assessment, and they were added to the council. In 2016, an Indigenous knowledge policy was established by the NWMO, and the Council of Elders and Youth issued the Declaration of the Keepers of the Land. In 2018, the NWMO released its reconciliation statement and in 2019 a policy was developed for engaging with Indigenous communities.

The purpose of the Council of Elders and Youth is to make sure that the land is cared for and that future generations who will inherit this project are cared for. Technical information is assessed and translated to be understandable by the elders to be relevant in their understanding of western culture. Recognition and understanding leads to informed understanding and informed decision-making.

Knowledge systems vary between the western and Indigenous cultures and are based on different concepts. For Indigenous knowledge, the focus is on understanding and relationships, while western knowledge focuses on definitions and repeatability. One system is not better than the other but both systems intertwine and overlap.

Together these systems create opportunities for western science, Indigenous knowledge and reciprocal learning and are based on mutual respect and understanding. There is importance in building trust, taking the time to build relationships in meaningful ways; continuing to meet with and spend time in the Indigenous communities. It is not only the strategic thing to do, but also the right thing to do. The challenge is how best to align the western knowledge system with the Indigenous knowledge system.

The reconciliation policy and continued learning strengthens Canada's relationship with Indigenous communities. Within the NWMO, a reconciliation assessment process was implemented allowing the organisation to consider reconciliation in its governance, in its human resources management and procurement processes and in doing things proactively and not reactively. Indigenous knowledge training has been implemented and by 2018, 85% of staff had received it.

There has been a lot learnt, but there is still a lot to learn in building trust and relationships between the NWMO and the Indigenous communities. This is crucial as the NWMO project cannot move forward without the informed consent of Indigenous communities.

Takeaways

- The NWMO has been engaging with Indigenous peoples since 2002.
- In 2005, an Elders Forum was formed, which is now called the Council of Elders. In 2014, the importance of youth was recognised, and they were added to the council.
- In 2016, an Indigenous knowledge policy was established by the NWMO, and the Council of Elders and Youth issued the Declaration of the Keepers of the Land.
- In 2018, the NWMO released its reconciliation statement.
- In 2019, a policy was developed for engaging with Indigenous communities.
- The NWMO continues in building trust and relationships between the NWMO and the Indigenous communities.

5.2. Good practices in stakeholder engagement and dialogue, including the intergenerational aspects of light water and Generation IV SMRs

SMR Action Plan pan-Canadian engagement

This presentation focused on Canada's SMR Action Plan. In 2018, Natural Resources Canada convened a ten-month stakeholder-driven engagement initiative that brought together provinces and territories, power utilities, industry and interested stakeholders to explore priorities and challenges related to the possible development and deployment of SMRs in Canada.

This report, the SMR Roadmap, found that SMRs could have significant economic and environmental benefits for Canada, and that success will rely on strategic partnerships across the sector and internationally. The report made over 50 recommendations from 55 contributing organisations. Partnerships will be key to success across the Canadian nuclear sector and internationally as well. The SMR Roadmap initiated Indigenous engagement.

The Action Plan builds on Canada's SMR Roadmap and resulted in 520 Actions with 119 participating organisations and ongoing Indigenous engagement.

While the federal government has responsibilities relating to nuclear energy, the decision to invest in electricity generation rests with the provinces. In December 2019, the Premiers of Saskatchewan, Ontario and New Brunswick signed a memorandum of understanding to collaborate on the development and deployment of SMRs. Alberta subsequently joined in 2021.

Under this agreement the provinces released a feasibility assessment of SMR implementation across provincial utilities. On 28 March 2022, Ontario, New Brunswick, Saskatchewan and Alberta released a joint strategic plan that outlines a path forward on SMR. The joint strategic plan highlights how SMRs can provide safe, reliable and low-emission energy to the benefit of the Canadian economy and population, while creating new opportunities to export Canadian knowledge and expertise around the world.

The SMR Action Plan Leadership Table provides a forum composed of the federal government, interested provincial and territorial governments, Indigenous representatives, industry (nuclear and high-emitting sectors), electric utilities, and non-governmental organisations to review progress and discuss strategic priorities as they relate to the development and deployment of SMRs.

The Indigenous Advisory Council for the SMR Action Plan is a 2-year initiative to provide a co-ordinated Indigenous voice on SMR development. It is a partnership project led by the First Nations Power Authority, Curve Lake First Nation and the North Shore Micmac District Council. It is funded by NRCan. It can advise Action Plan participants (nuclear sector) on actions and priorities (could include engagement, waste, education, transportation, equity, economic inclusion) and provides representatives to the SMR Action Plan Leadership Table. It does not replace SMR engagement and consultation.

The SMR Action Plan Leadership Table will meet biannually and work with Canada’s nuclear energy sector to develop an SMR sector and supply chain that will benefit Canadians economically, environmentally and socially.

The audience commented on the path forward with regard to waste and observed that the leadership table provides a good mechanism to point at priorities, with waste being one of them.

Takeaways

- What is needed in Canada is a thoughtful, collaborative and ambitious pan-Canadian net zero strategy that will create wealth in every region in the country, while ensuring that climate goals are achieved.
- Citizens are looking to get on with building an economy that will serve citizens’ needs and will protect the planet in the long term.
- Vigorous discussion and debate results in progress being made on reducing carbon emissions in line with science.
- True collaboration, almost by definition, requires compromise and this applies to every file in government, including the pathway to net zero.

- It is important to remain united in the common goal of lowering emissions at a pace and scale that is consistent with science.

Mutual benefits: Contemporary Indigenous engagement

This presentation focused on Indigenous engagement associated with Global First Power's intention to construct, own and operate a micro modular reactor (5 MWe) at the Chalk River Nuclear Laboratories. Global First Power is owned by OPG and Ultra Safe Nuclear Corporation and operations are planned to begin in 2026.

As part of this project, OPG is responsible for the project co-ordination, the environmental assessment, for overseeing licensing and for public and Indigenous consultation.

The speaker referred to public scepticism of nuclear technologies and that factors for this scepticism include institutional credibility, information sharing and communication processes. It was noted that the nuclear industry did not conduct engagement well in the past, and that things need to be done differently.

The difference in terminologies between consultation, engagement and participation were presented. Consultation is a legal duty that lies with the Crown while engagement refers to a vendor or operator's requirement to engage Indigenous communities. Participation for Indigenous communities can mean fund transfers and equity partnership or ownership.

Barriers to engagement include lack of motivation or time, information deficiencies, lack of resources at the community level, unequal opportunities to participate and lack of input to the final decision.

Progress has been made in Indigenous relations. Internationally, the United Nations Declaration on the Rights of Indigenous Peoples was adopted by Canada in 2021. With respect to the legacy in Canada of the residential schools, the Truth and Reconciliation Commission was created between residential schools' survivors, the Assembly of First Nations, Inuit representatives and the parties responsible for creation and operation of the schools: the federal government and the church bodies.

The Truth and Reconciliation Commission's mandate was to inform all Canadians about what happened in residential schools. It prepared a comprehensive report on the policies and operations of the schools and their lasting impacts. The final report included 10 principles for reconciliation and 94 calls to action that speak to all sectors of Canadian society.

Meaningful partnerships with Indigenous communities have been made since 2009; Obishikokaang Waasiganikewigamig/Lac Seul generating station, Amisk-oo-Skow agreement, Coral Rapids power and Nanticoke solar facility. Relationships with Indigenous communities require meaningful interactions, capitalise on common understandings, and include equity ownership.

Takeaways

- Factors of public scepticism in nuclear technologies include institutional credibility, information sharing and communication processes. The nuclear industry did not conduct engagement well in the past and things need to be done differently.

- Consultation is a legal duty that lies with the Crown while engagement refers to a vendor or operators' requirement to engage Indigenous communities. Participation for Indigenous communities can mean fund transfers and equity partnership or ownership.
- Barriers to engagement include lack of motivation or time, information deficiencies, lack of resources at the community level, unequal opportunities to participate and lack of input in the final decision.
- Progress has been made in Indigenous relations. Relationships with Indigenous communities require meaningful interactions, capitalising on common understandings and including equity ownership.

Indigenous engagement in the nuclear industry

This presentation by the NWMO reviewed engagement with Indigenous communities and observations on Indigenous engagement within the nuclear industry.

The location of an Indigenous community contributes to the type of engagement.

For example, in the north there is not a lot of awareness of the nuclear energy industry unless they are located in proximity to a nuclear facility. In Ontario, northern communities do not understand the energy mix of the province and are generally not aware that the electricity that powers their homes comes from nuclear energy. For northern communities, engagement must start from scratch, and it takes time to educate people and dispel myths.

In the south, there is much more awareness because of the location of Ontario's nuclear energy facilities. Most Indigenous communities have participated in the industry and are aware of its legacy issues since engagement practices have changed since the building of the first nuclear stations. Today, Indigenous rights are a bigger part of any and all discussions.

In looking for host communities for the NWMO's DGR, 22 communities expressed interest in learning more and exploring their potential to host the project. The NWMO had to reach out to Indigenous communities to inform them of the project.

Through technical studies and engagement efforts, the list has been shortened and currently two potential siting areas remain, the Wabigoon Lake Ojibway Nation Ignace area and the Saugeen Ojibway Nation south Bruce area, both in Ontario. The DGR project is unique in that it requires a location that is safe and requires partnership with the local and Indigenous communities.

Discussions to date have focused on protecting water, the environment and the earth. Once the NWMO has identified an appropriate site and willing hosting community, the NWMO will begin to engage with Indigenous communities along proposed transportation routes.

For Indigenous engagement to succeed, it is important to know the community, be genuine and patient and respect the time that is given to establish a rapport. It is also important to remain humble and grounded and to understand the demands that the communities have, including in governance. It must also be realised that what works with one community does not necessarily work with other communities.

To achieve success, support from organisation leadership is required. Senior management must be informed of risks and progress. A rapport with the regulator and government is required, as is hiring the right people.

Takeaways

- The location of an Indigenous community contributes to the type of engagement required.
- Indigenous communities have demands including governance that must be accommodated when planning engagement.
- Engagement with Indigenous communities may require that organisations proactively reach out to them.
- What works with one community does not necessarily work with other communities.
- To achieve success, support from organisation leadership is required.

SMRs and public engagement

This presentation discussed how public engagement is conducted.

For SMRs, key questions include how different SMR public engagement is from traditional nuclear engagement (new technology, new locations), what makes for an effective process of engagement, and what the legal and political distinctions are between engagement between Indigenous peoples and non-Indigenous communities.

Generalised engagement questions include what two-way engagement really involves, what issues engagement should address, how a community is defined in a world where there are many different social, physical and cultural groups that may be impacted, and whether those communities are the only groups that need to be engaged.

Policymakers are required to somehow balance expertise with democracy. Experts make recommendations based on science and engineering, not on the democratic desires of the public. Balancing this becomes difficult for government when the issue is contentious, such as for nuclear. Governments utilise a public consultation process in order to determine public acceptance. In relation to public participation, key definitions include inform, consult, involve, collaborate and empower.

Archon Fung identified a framework for understanding and comparing different forms of public consultation. Fung showed that there are three dimensions within which a public consultation process can occur: who participates, how participants communicate with one another and make decisions together, and how discussions are linked with policy or public action.

Examples of poor consultation include the Northern Gateway pipeline (2016) and the Trans Mountain Pipeline (2018), projects that were quashed by the Federal Court of Appeal for insufficient consultation with Indigenous peoples. This resulted in the loss of billions of dollars in lost revenue and heightened political tensions between Alberta (the oil producing province), British Columbia (the province where the pipeline travelled) and the federal government.

In relation to nuclear energy, poor consultation occurred in the Saskatchewan Uranium Development Partnership (2009), which was created by the government and led by nuclear experts. It included recommendations for exploration and mining, uranium upgrading, nuclear power generation, used fuel management, and R&D. Consultation activities included:

- a major stakeholder conference in Saskatoon;
- public hearings in Saskatoon and Regina;

- thirteen community meetings across the province;
- opportunities for individual stakeholder organisations to provide oral and/or written submissions;
- opportunities for presentations from First Nations and Métis groups;
- a consultation website.

Over 2 600 people attended the public meetings and almost 1 300 people responded by letter/email. The results were overwhelmingly negative with 85% opposed to nuclear power generation.

However, there were flaws in the process:

- 98% of responders viewed the public consultation process as inadequate.
- 88% believed that it would have no impact on the government.
- Media reported that 85% of Saskatchewanians opposed nuclear power generation, but it was actually 85% of responders who attended public meetings or submitted letters.
- No representative sample public opinion polling occurred.
- There was clear evidence of double counting by respondents (each speaker or letter was counted separately, even if there were multiple efforts by the same person).
- Responses from large organisations (e.g. the Saskatoon Chamber of Commerce, Cameco) counted the same as responses from small organisations (e.g. Fellowship for Reconciliation and Peace, Singers of the Sacred Web) or even an individual.
- There was no attempt to evaluate the quality or factual accuracy of the responses.

One Canadian organisation that has developed a new approach to public, community and Indigenous engagement is the NWMO, a not-for-profit corporation established by Canadian Parliament and owned by Canada's nuclear energy producers. The project is to locate, construct and operate a deep geological repository for used nuclear fuel. The NWMO is proceeding in stages in an open, transparent and inclusive manner, taking the time needed to collaboratively plan and confirm each step through an ongoing dialogue with the public.

Takeaways

- SMRs are a combination of existing nuclear and new technology. But they may be decentralised so their location and distribution may complicate public engagement.
- All major energy projects require public engagement.
- There are different forms of public engagement, ranging from tokenism to citizen power.
- There are substantial political and financial costs to not doing engagement properly.

- The NWMO's site selection process for permanent nuclear waste may be a model for SMR engagement.

5.3. Panel discussion on key takeaways and recommendations

The panel and the presenters discussed the key takeaways/recommendations from this session, which was followed by questions from the audience. The discussion was rich in nature, and it explored topics such as the stakeholder consultation in Canada and elsewhere.

The Chair of the session stated that NWMO provides a good example of public engagement. In the context of radioactive waste management, some questions do not yet have clear and definitive answers. Therefore, it is important that organisations and communities are able to continually listen and learn from one another. Organisations that are leading engagement activities may have to come to terms with the possibility of needing to have uncomfortable conversations. They should aim to cultivate honest relationships and should remain as genuine and authentic as possible. Accountability is a key value that needs to be expressed during this dialogue process and be accompanied by follow-up actions as needed. There is an opportunity that can be seized when not all the answers to the matter in question are available, as it provides an arena for each party to listen to the truth and perspectives of the other. As an example, the Indigenous community does not conceptualise time as linear but as multidimensional. This difference in perspective affects the way long-term decisions are made.

Consultation in Canada

The consultation policy in Canada is transparent now because of lesson learnt from past actions that were not successful. In the past, consultation activities informed municipalities first and then informed Indigenous communities. Procedures like the Canadian Impact Assessment Act that emphasise early consultation should be embraced, not criticised. This procedure has contributed to a culture shift towards real dialogue. As part of this dialogue process, engagement at the grass roots level is as important as the engagement at the higher/decision-making level or at the youth level. Acceptance at all levels must be established for meaningful engagement to take place and the right approach must be pursued. This process needs to start with a genuine desire to listen and be honest.

A question was raised about a specific workshop that occurred on "community engagement". The panel responded that the workshop was not very successful and contributed to changes in engagement approaches. Engagement process changes were also brought through lawsuits, constitution changes and public acceptance of court decisions. The public took a while to accept these changes as being reasonable. In past meetings, there were only a few female millennials present during consultation; however, now the youth have greater access to information. The panel underlined that the ancestors stood up for their rights and that they signed treaties with the intent of sharing the land. When the terms of the treaty were not fulfilled, they challenged the government. As a result, changes in the engagement process can be seen compared with 20 years ago, and in 40 years there may be further changes.

Questions were raised as to how First Nations are kept continuously involved in all projects now that there is no nuclear without their consent. The panel responded that Indigenous peoples are not being left out from decision-making conversations anymore. Nowadays, organisations understand the value of diversity and diverse perspectives in solving complex problems. The Indigenous community has the capacity in the community to learn about a project, and be participants in it, and not just to check a box.

The panel discussed the point regarding Canada lobbying Japan to take its used fuel. The lesson learnt to be drawn from this activity is that there needs to be a strong connection between the benefits for the community and where the spent fuel is to be located. There needs to be a different vision for the organisation and this vision should not be rooted solely in the need to find a storage space for waste but rather it should also be based on the potential impacts for future generations.

Consultation elsewhere

The question was raised as to what consultation steps should be followed for a new organisation developed in the United States. The panel noted that a lot can be learnt from past failures. The panel advised that the first step should start with the First Nations communities. The Impact Assessment Act (in Canada) should be considered an opportunity rather than an administrative burden.

The audience noted that in the United States a lack of understanding often leads to litigation. An example of this is the Handford site, which is considered sacred land and had its settlers removed from the land. This case is still in the negotiation phase; however, the Indigenous populations are not present in these negotiations. A question was asked about what the differences are between the United States and Canada. The panel noted that there are more differences than similarities between the two countries. Among the differences between the US and Canadian systems, it was noted that Indigenous rights are embedded in the Canadian constitution and there are more Indigenous peoples in Canada than in the United States.

The audience questioned how Indigenous principles and values align with minimising the spread of nuclear power? The panel noted that support for nuclear energy remains low in some communities and that honest conversations are needed regarding the impacts of green energy such as wind and solar. It was stated that wind and solar are not as clean as may be believed, while nuclear energy is not as bad/damaging as sometimes portrayed. In order to have a real conversation, the advantages and benefits of nuclear, wind and solar energy must also be included in the scope of the discussion.

Lastly, the panel noted that the waste was not created by Indigenous peoples and therefore it is not their problem. However, Indigenous people have a role and interest in protecting the Earth, so they should be involved. The conversation is uncomfortable and difficult, but it should be had.

6. Session 5 - Summary and closing remarks

6.1. Summary and closing remarks

The workshop Chair noted that the main concept is getting comfortable with being uncomfortable. Proper engagement is required with Indigenous communities and stakeholders. The Chair noted that the workshop had 150 in-person attendees and 400 online attendees representing 50 countries.

6.2. Closing address

Lou Borian, vice president of corporate affairs at CNL, provided the closing presentation. This presentation provided insight into the work that CNL is conducting to advance nuclear science in Canada.

The CRL site was described as Canada’s national nuclear laboratory, with over 50 laboratories on a 9 000-acres campus and with labs and project sites across Canada. CNL has a diverse team of over 500 PhDs and researchers with a broad portfolio in science.

CNL is a private sector company with a contract to operate and manage the CRL facility on behalf of Atomic Energy of Canada Limited, a federal crown corporation. Its vision is to restore and protect the environment from legacy sites and operations, support the power reactor industry and improve the health of Canadians though nuclear related activities.

The presentation closed with a look at the significant revitalisation that is occurring. This includes new facilities such as the hydrogen research centre, the materials science complex, the tritium laboratory complex, the advanced nuclear materials centre, and significant infrastructure and supporting facility renewals.

The workshop was closed by Elder Thomas Louttit who provided closing remarks and a closing ceremony.

6.3. Workshop summary

The scope of the workshop was broad, covering technical, legislative and social perspectives. Questions from the audience ranged widely in topic areas, as did the panel discussions at the end of each session. Readers of this document are encouraged to review the presentations and other materials that are provided on the NEA workshop website to gain a complete understanding.

A major focus of the workshop was on the implementation of radioactive waste management and decommissioning strategies in light water and Generation IV SMRs. This included exploring the types of SMR technologies, the potential for fuel recycling, and research that is being conducted in relation to design and fuel concepts. As there is a wide variety of designs and fuel types, the potential uses for SMRs (thermal or electrical generation) were discussed, including in some cases conceptual facility footprints.

With respect to operational and decommissioning wastes, potential strategies for the management and disposal of wastes and for the accommodation of waste were reviewed. The workshop highlighted the need for more information with respect to reactor design and fuel characteristics to assess the types of waste forms that might be generated, and to evaluate how existing waste management practices could either be adopted or modified to allow for the safe storage and disposal of wastes. To that end, early dialogue is needed between the designers, regulators, operators and other stakeholders to address this information gap.

One significant factor that was raised is decentralisation, as the multiplication of many SMRs across a large geographical area might require more local waste management facilities or increased long-distance transport of wastes to one or more centralised storage or disposal facilities. This issue involves both technical and social factors. The types and forms of transport casks were discussed, including the potential need for new cask designs or for adapting existing approved designs.

Ongoing challenges that were raised include restrictive government policy, the licensing requirements of nuclear regulators, available data on new fuel characteristics and engagement of the public and Indigenous communities, including the need for informed consent.

Many countries provided updates on the state of national regulation, progress made in dealing with existing inventories of radioactive waste and used nuclear fuel, and on lessons learnt that could be applied towards emerging new technologies now being considered. The storage, transport and disposal of existing inventories of radioactive waste and used nuclear fuel are currently well understood and these materials are safe for placement in existing facilities. However, more work needs to be done on the impact that some types of used nuclear fuel and radioactive waste from SMRs may have on existing waste facilities, and how they can interface with repository facilities that are still in the conceptual design process.

In relation to public consultation, it was noted that continued dialogue with all stakeholders early in the design and decision-making process could build trust and consensus.

The role of Indigenous communities and other key stakeholders and the need for a consent-based process was also part of this workshop. Several speakers spoke to the issues of the past and near past, current relations with Indigenous communities and the need to share resources and develop meaningful relationships. The transformation has begun in the building of relationships from the Canadian federal government and from the agencies and corporations who engage with Indigenous communities. Processes and policies have been developed and are still undergoing transformation to recognise and enshrine Indigenous rights. To achieve net zero, new nuclear energy facilities are required and informed consent needs to be addressed in this process.

Key takeaways/considerations:

- A better understanding of reactor design is needed.
- A better understanding of the management of all wastes generated from the facility lifecycle is needed including: site preparation, construction, operation and decommissioning, considering interim storage, recycling, waste minimisation waste treatment, transport and disposal.
- Material selection for key reactor components needs to be evaluated. The reduced size of the reactor core could increase risks of activation of materials and have the potential to increase waste volumes during operation and decommissioning.

- A better understanding of spent nuclear fuel characteristics is needed. Different fuel forms, different levels of enrichment, different levels of burnup, varying levels of decay heat, radioactive source term and isotopic composition of wastes pose a challenge.
- A better understanding of TRISO fuel management is needed.
- A better understanding of transport cask design is needed. Transport cask compatibility with new fuel types (e.g. HALEU) needs to be examined (considering shape, heat load and fissile content). For fresh fuel with enrichment of >6.5%, no licenced transport package exists (although existing packages may be used with modification for enrichments up to 10%).
- A better understanding of spent fuel treatment options is required. More research is needed to convert non-storable, non-transportable, spent fuel into a form that would meet disposal acceptance criteria (e.g. molten salt fuel that may have to go through chemical conversion or stabilisation).
- Recycling approaches for new fuel types needs to be examined in order to reduce spent fuel volumes (for example, high-temperature gas reactors are likely to generate more used nuclear fuel than current light-water reactors).
- Graphite and ^{14}C waste management options need to be carefully evaluated.
- Careful examination of lessons learnt from various countries is needed. For example, the United States has experience in used nuclear fuel and high-level waste management from a wide variety of reactor types (fast reactors, molten salt, high-temp reactors/TRISO).
- Early Indigenous community/stakeholder outreach is recommended. The early engagement of Indigenous communities, the general public and other key stakeholders is required to address the need for a consent-based approval process for the siting and construction of new nuclear facilities, or for the modification to existing nuclear facilities.

6.4. Programme committee

Programme committee members and the NEA Secretariat collaborated in the planning, preparation and conduct of the event:

Programme committee members:

- BRADY, Daniel, CANADA - NRCan
- FORINASH, Betsy, UNITED STATES - Environmental Management, DOE
- FRATONI, Massimiliano, UNITED STATES – University of California, Berkeley
- LANDAIS, Patrick, FRANCE - CEA – High Commissioner
- LIETAVA, Peter, CZECHIA - State Office for Nuclear Safety
- LORENCEZ, Carlos, CANADA - CANDU Owners Group
- MCKINNEY, James, UNITED KINGDOM – NDA (Workshop Chair)
- MECKE, Julie, CANADA - Radioactive Waste for NRCan

- OUE, Shirley, CANADA - Radioactive Waste for NRCan
- PRIETO SERRANO, Nuria, SPAIN - ENRESA

NEA:

- ALONSO DE VILLAPADIERNA, Maria Teresa, Division of Radioactive Waste Management and Decommissioning (RWMD)
- CHEBAC, Riccardo, RWMD
- GRASSI, Gabriele, Division of Nuclear Science and Education (SCI)
- MEKKI, Soufiane, RWMD
- MERCIER, Alexia, RWMD
- SMADJA, Lisa, RWMD
- TADESSE, Rebecca, RWMD
- YILMA, Haimanot, RWMD

Rapporteur: BARKER, Robert, Ottawa, Canada

6.5. Venue

The workshop took place at the Lord Elgin Hotel in Ottawa, Ontario, Canada, 100 Elgin Street, K1P 5K8 from 7-9 November 2022. The following day on 10 November 2022, a select number of participants went on a tour of CRL, which is owned by Atomic Energy of Canada Limited and operated by CNL.

References

NEA (2013), *The Economics of the Back End of the Nuclear Fuel Cycle*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_14764.

UK Government (2019), 2019 Inventory for Geological Disposal - GOV.UK, www.gov.uk/government/publications/2019-inventory-for-geological-disposal.

Annex A. Programme

Programme overview

Monday, 7 November 2022

Session 1. Understanding the functioning of major SMRs/advanced reactor technologies and fuel cycles

1.1. Overview of mature SMR/advanced reactor technologies and associated fuel type

This session will focus on understanding the functioning of major SMRs/advanced reactor technologies, with the main differences expected in the function of the technologies and mode of operation (e.g. fuel type) compared with contemporary designs.

1.2. Key attributes of SMRs/advanced fuel type, and design considerations and implications for decommissioning and radioactive waste management

This session will explore the key questions designers need to consider when developing a new fuel that has not been evaluated by waste acceptance criteria. For example: are deep geological repositories capable of taking this kind of waste? Should that be considered now? What challenges/issues may arise that are different compared to traditional reactor oxide fuels during transportation, management and disposal of spent fuel or by-products of spent fuel treatment (recycling/ conditioning)?

1.3. Panel discussion on key takeaways and recommendations

This panel invites the previous presenters to develop one slide with key takeaways/recommendations and proceed with to a panel discussion, during which the floor will be opened for questions from the audience will be invited.

Session 2. Storage and transportation of spent fuel and radioactive waste in SMRs/advanced reactor designs

2.1. Overview of work activities on fuel storage and transportation

This session will highlight the challenges associated with fuel storage and transportation and their potential applicability to new fuel types (e.g. dual cask, criticality issues and environmental concerns).

Wednesday, 9 November 2022

3.4. Panel discussion on key takeaways and recommendations

This panel invites the previous presenters to develop one slide with key takeaways/recommendations and proceed to a panel discussion, during which questions from the audience will be invited.

Session 4. Key considerations for communities, Indigenous peoples and stakeholder involvement

4.1. Indigenous community/tribal nation perspectives on the potential deployment of SMRs and advanced reactor technologies

4.2. Good practices in stakeholder engagement and dialogue, including the intergenerational aspects of SMRs/advanced reactors

4.3. Panel discussion on key takeaways and recommendations

This panel invites the previous presenters to develop one slide with key takeaways/recommendations and proceed to a panel discussion, during which questions from the audience will be invited.

Session 5. Summary and closing remarks

Thursday, 10 November 2022

Site Visit to Canada's National Nuclear Laboratory

Canadian Nuclear Laboratories (CNL) is Canada's premier nuclear science and technology organisation, and a world leader in developing nuclear technology for peaceful and innovative applications. Using its unique expertise, CNL works to restore and protect the environment, advance clean energy technology, and facilitate medical breakthroughs that continue to improve the health of people around the world.