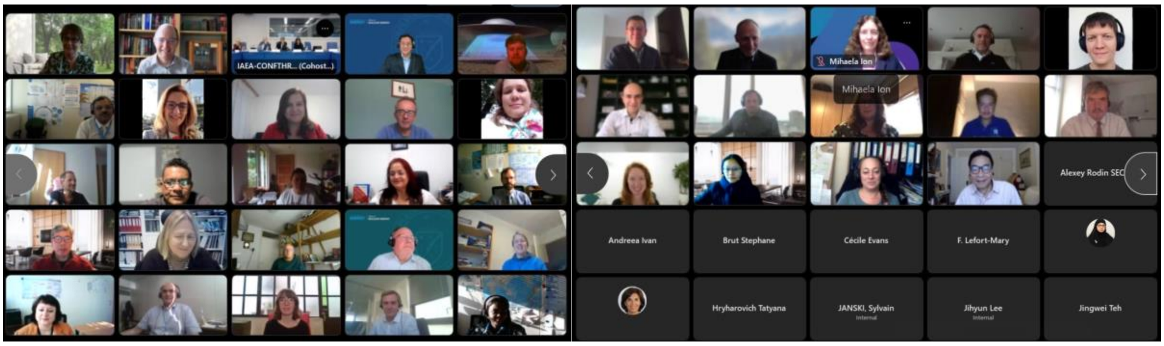
IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Technical Meeting on Back End of the Fuel Cycle Considerations for Small Modular Reactors



IAEA Headquarters; Vienna, Austria
and virtual participation via Webex

20 – 23 September 2022

Meeting Report

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1. INTRODUCTION

The Technical Meeting on Back End of the Fuel Cycle considerations for Small Modular Reactors was convened from 20th to 23rd Sep 2022 in hybrid format (part of the delegates in-person and part of them participating virtually via Webex). It was attended by 107 participants from 32 Member States, and 3 International Organizations. The attending countries and organizations were Argentina, Armenia, Belarus, Bolivia, Bulgaria, Canada, China, Czech Republic, Egypt, Ethiopia, Finland, France, Hungary, India, Japan, Jordan, Lithuania, Malaysia, Netherlands, Pakistan, Philippines, Poland, Romania, Russian Federation, Singapore, Slovenia, South Africa, Sudan, Sweden, Thailand, United Kingdom, United States of America, Uzbekistan, the European Commission (EC), the OECD/Nuclear Energy Agency and the European Repository Development Organization (ERDO).

There is an increasing interest in Small Modular Reactors (SMRs) and their applications, in part due to their consideration as a low carbon energy source in the climate change mitigation plans of many Member States. SMRs are newer generation reactors designed to generate electric power typically up to 300 MWe and for non-electrical industrial applications (e.g., water desalination and heat generation for industrial processes). According to the IAEA Booklet on Advances in SMR Technology Developments, complementary to ARIS and published in 2022, there are more than 80 SMR concepts currently under development, spanning a significant range of reactor technologies. The SMR concepts can be deployed in a variety of configurations, ranging from single-unit installations to multimodule plants with a different degree of modularization across designs to suit the requirements of the operator.

SMR concepts vary from evolutionary variants of Light Water Reactors (LWR-SMRs, either land or marine based), that benefit from many decades of operating experience of the current fleet of LWRs; High Temperature Gas Cooled Reactors (HTGR-SMRs); Liquid Metal Fast Reactors (LMFR-SMRs) and molten salt reactors (MSR-SMRs). SMR designs use a variety of coolants (water, liquid metal, molten salts) and fuel forms (oxide/ceramic, metal, TRISO, liquid fuel salts, etc.) having different Technology Readiness Levels (TRLs) and fuel compositions (UOx (LEU, HALEU); Mixed U and Pu (oxide, metal, or salt); kernel particles; etc.)

While much focus has been given to aspects of SMR deployment such as reactor concepts, engineering, economics, infrastructure, safety, etc., the fuel cycle, and in particular the management of Spent Nuclear Fuel (SNF), appears to have had limited consideration. As the SMR concepts are becoming more refined, it is an appropriate time to start identifying the challenges, opportunities, gaps, and issues for managing spent fuel from SMRs during all stages of the back end of the fuel cycle such as storage, transportation, reprocessing & recycling, and disposal.

The management of spent fuel is very dependent on the characteristics of the nuclear fuel relating to its enrichment, matrix and composition, and its irradiation history (e.g., burnup). Spent fuels coming from SMRs will have different characteristics and irradiation histories that will require either adaptation of currently implemented technologies or new developments for all stages of the back end of the fuel cycle to accommodate higher thermal outputs and criticality risks, different radionuclide inventories, new matrices and cladding behaviors, etc., implying the need for R&D, demonstration projects and licensing to ensure that the main safety objective is met.

In its 17th Meeting in April 2019, the Technical Working Group on Nuclear Fuel Cycle Options and Spent Fuel Management (TWG-NFCO) recommended that "*The next update of the Advances in Small Modular Reactor Technology Developments report should consider technologies for managing SNF from SMRs. This update should not only consider the reactor technology, but also the backend infrastructure that would be needed to support SMRs' deployment - including transportation, storage, recycling, and disposal technologies. Newcomer countries should be made aware that, as with all reactor types, the management of SNF from SMRs needs to be fully considered. Nuclear fuel cycle* *aspects, in particular the backend, should be integrated into all IAEA working groups that are looking at SMRs*".

Based on those recommendations, a Technical Meeting was organized from 20 to 23 September 2022 to facilitate the exchange of information and discussions regarding the management of spent fuels coming from all envisaged SMR technologies to enable experts to collaboratively identify the opportunities and challenges faced at all stages of the back end of the fuel cycle (e.g., storage, transportation, reprocessing & recycling, and disposal), the gaps in current infrastructures and the knowledge required to ensure an integrated approach to the overall spent fuel management strategy, as well as the potential ways to move forward in addressing them in the near, medium, and long terms.

The Technical Meeting Agenda and the list of participants are included in Annex I. Summaries of the different sessions were prepared by the assigned reporters/co-chairs.

2. SUMMARIES OF SESSIONS

2.1. SUMMARY OF IAEA PRESENTATIONS (Prepared by Mr Surik Bznuni, Armenia)

IAEA (NPTDS, Nuclear Power Technology Development Section), 2022 IAEA SMR ARIS Booklet on Advances in SMR Technology Developments – Mr Hadid Subki

Mr Subki presented characteristics and attributes of SMRs and the status of advances on SMR technologies. Typically, SMRs are advanced reactors that produce up to 300 MWe, built in factories and transported as modules to sites for installation as demand arises. The key attributes of SMRs are six: economic, modularization, flexible application, smaller footprint, can be replacement of ageing fossil-fired plants and can be potentially part of hybrid energy systems. SMRs can be classified in various ways according to technology and capacity. The IAEA has summarized the current status of these SMR developments in the IAEA ARIS (Advances in Small Modular Reactor Technology Developments) SMR Booklet, 2022.

A subset of SMRs are microreactors (1-20 MWe capacity) that have common features with the rest of SMRs. The following specific characteristics and applications of microreactors were considered in the booklet:

- Inherent and passive safety features
- Substantially lower upfront capital costs
- Much smaller footprints, reduced-sized or even eliminated EPZ (Emergency Planning Zones)
- Rapid deployability from modularity (even an entire reactor)
- Spent fuel smaller in size (probably easier to manage)
- Scalability, resiliency, self-regulating
- Potential to operate in island-mode & to black-start
- High transportability from mobility
- Long refueling interval

The IAEA ARIS SMR booklet 2022 includes not only information on the technical aspects of SMR designs, but also some considerations for fuel cycle approaches, waste management and disposal plan by SMR type.

IAEA (NPTDS, Nuclear Power Technology Development Section), The IAEA Platform on SMRs and their Applications: Progress and Achievements after one year – Mr Stefano Monti

Mr Monti introduced the IAEA's Platform on SMRs and their Applications and elaborated on the progress of its development after one year. This Agency-wide platform has been developed from Member States requests to coordinate and optimize the Agency effective and efficient support to Member States, international organizations and stakeholders dealing with SMRs and willing to cooperate with the IAEA.

First achievement is an actual and effective coordination of all the agency activities on SMRs and their applications throughout the relevant Departments and Offices. Second was to establish a medium term strategy thorough analysis of the ongoing and planned IAEA projects, initiatives and activities on SMRs and their applications. Third was to prepare a high level "SMR Booklet: A New Nuclear Energy Paradigm", currently available at the IAEA on-line preprint repository. The target audience for this material is policy makers and government officials interested in SMRs. Fourth achievement was to create the SCORPION SMR portal that gathers external information on SMRs. Fifth achievement is the new TC-Interregional project INT2023 Project (2022-2025). The main objective of this project is to improve technical knowledge, capacity building and safety review capability in developing countries addressing the fundamental aspects of SMRs and their electric and non-electric applications. Sixth achievement was the creation of Agency-wide task forces to work in specific activities related to SMRs.

An SMR platform annual report was delivered for the period 2021- 2022 summarizing the relevant work carried out and managed by all IAEA Sections working on SMRs and their applications.

IAEA (NFCMS, Nuclear Fuel Cycle and Materials Section), IAEA On-going Activities on Spent Fuel Management – Ms Amparo González Espartero

Ms González Espartero presented on-going IAEA activities to address spent fuel management challenges, that can be summarised as the increasing of storage periods that requires to put in place ageing management programmes to confirm spent fuel integrity and to ensure that the systems, structures and components keep the safety functions in place; transportability of storage packages after long storage periods; implementation of multi-recycling of U/Pu in LWRs at industrial scale; demonstration and scale-up of multi-recycling through advanced fuel cycles for innovative reactors (Gen-IV); and to accommodate the management of new spent nuclear fuels (e-ATFs and SNF from SMR technologies).

The IAEA is conducting Coordinated Research Projects (CRPs) to address those issues, some of them are already closed and documented ("Demonstrating Performance of Spent Fuel and Related Storage System Components During Very Long Term Storage" TECDOC-1878; "Spent Fuel Performance Assessment and Research" (SPAR IV), TECDOC-1975, and "Ageing Management Programmes for Dry Storage Systems", TECDOC under preparation) and others are active and still open for proposals ("Spent Fuel Characterization" T13018, "Spent Fuel Research and Assessment (SFERA)" T13020, and "Performance Assessment of Storage Systems for Extended Durations (PASSED)" T13019).

The "IAEA Guidebook on Spent Fuel Storage Options and Systems, 3rd Edition" IAEA-NTR-240, has been recently made it publicly available through the IAEA Pre-print Repository in 2022 and gathers information on current situation on spent fuel storage systems and options, describing the main features of storage systems, showing the distribution of the current SNF inventory in the different storage systems by regions and by countries, a harmonised scheme of dry storage systems and examples of the corresponding commercially available systems.

Detailed information on these and other IAEA activities on SNF recycling, IAEA International Conferences, e-Learning Course on spent fuel management and IAEA webinars on spent fuel management can be found at the IAEA Spent Fuel Management Network public page.

UK (NNL), Information on the IAEA TM on Back End Opportunities and Challenges for Spent e-ATFs Management – Mr David Hambley

Mr Hambley presented a summary of an IAEA Technical Meeting (TM) held virtually back in June 2022 which was focused on back end opportunities and challenges for managing spent Evolutionary Accident Tolerant Fuels (e-ATF). Some of those fuels are likely to be deployed in the current fleet of reactors and in some of the different SMR technologies in the near term. E-ATFs can be licensed under existing regulatory guidelines and typically involve fuel for LWRs (large or small); coated zircaloy fuel (e.g., FeCrAl) and potentially doped UO_2.

The Technical Meeting pointed out that there is a lot of work underway to understand the impact of e-ATFs on back end activities. There was a common recognition of the need for irradiated fuel characterization data and testing to validate the models that support the back end fuel cycle stages. The importance of multilateral cooperation was remarked upon by several participants.

Currently, there are lead assemblies under test irradiation in multiple reactors and various industrial implementations were proposed such as batch loading which represents a significant shift from lead test assemblies and qualified commercialized manufacturing process. For storage and transportation, data is needed to support the use of proven methods for criticality, shielding, etc.; fatigue, mechanical behaviour and long term degradation of coated claddings and dryness determination.

For reprocessing, shearing behaviour of chromium coated clad needs investigation to determine whether additional fines are produced. Routing of the fines and impact on plant with respect to corrosion and PUREX performance need to be determined. The presence of chromium in raffinate may impact vitrified glass quality with impact on disposal routes. The meeting participants came up with some recommendations for future IAEA activities, such as the organization of a workshop to identify needs and collaborative R&D opportunities to underpin spent e-ATF management.

IAEA (Department of Nuclear Safety and Security, Division of Installation Safety, NSNI), Consideration of Non-Water Cooled Reactors and SMRs in the IAEA Safety Standards – Ms Paula Calle

Ms Calle presented results of the analysis of the applicability of the IAEA safety standards to non-water-cooled reactors and SMRs. The approach to conduct the review was to identify areas of novelty compared to LWRs, gaps as well as areas where current safety standards might not be applicable.

The following high-level conclusions were highlighted:

- Some safety approaches focus on conventional LWRs and do not cover SMR specificities
- There is lack of experience on practical application
- First of a kind (FOAK) issues are not properly considered
- New modes of failures, equipment failures or phenomena are not covered

In Construction and Manufacturing area, advanced manufacturing and factory-based aspects need further consideration. In Commissioning and Operation, Accident Management areas of alternative operating models and implications from novel and FOAK need further consideration. In Leadership and Management for Safety areas, oversight of manufacturing if operator is not known and novel features implications on management system need further consideration. In Legal and Regulations area, international cooperation and impact of deployment model on regulatory oversight need further consideration.

In Fuel Cycle Facilities area, the Safety Standards cover current fuel fabrication processes, but additional Safety Guides would need to be developed to cover the fabrication of advanced fuels and reprocessing of non-WCR fuel once there is sufficient knowledge and experience on these processes. Until such a point is reached, the guidance in SSG-43 is seen as sufficiently general to guide the safety of nuclear fuel cycle facilities associated with Evolutionary and Innovative Designs (EIDs).

IAEA is planned to develop new safety guide "Safety Demonstration of Innovative Technology in Power Reactor Designs" to address FOAK issues.

IAEA (Department of Nuclear Safety and Security, Division of Nuclear Security, NSNS), Security Considerations for Back-End of Nuclear Fuel Cycle for SMRs – Mr Tariq Majeed

Mr Majeed presented the IAEA perspective on security considerations for back end of nuclear fuel cycle for SMRs. General conclusion is that for LWR-SMRs back-end security considerations are mainly the same as for conventional LWRs. Innovative SMRs with exotic design solutions, like molten salt reactors could pose specific challenges on providing security. Development of new IAEA technical documents related to security of SMRs is in progress.

IAEA (Department of Safeguards, Division of Concepts and Planning, SGCP), Safeguards Considerations for SMR Fuel Cycles – Mr Kerrin Swan

Mr Swan presented safeguards considerations for SMR fuel cycles. It was highlighted that all SMRs and related nuclear fuel cycle facilities, built in States with comprehensive safeguards agreements – even prototypes – will need to be safeguarded, regardless of the size, technology, or State of origin.

The following main challenges for SMRs safeguards were identified:

- New fuels and fuel cycles as Th/U-233, RepU, MOX, TRU fuels, pebble bed, prismatic core, pyro-processing and other new processes.
- New reactor designs: molten salt, fast neutron, micro-sized, etc.
- Longer operation cycles: continuity of knowledge of nuclear material must be maintained (for example, between refueling), high excess reactivity of core which could be used for target accommodation.
- New supply arrangements as factory sealed cores, transportable power plants, transnational arrangements (need for design verification at State of origin and receiver State, IAEA sealing).
- New spent fuel management: storage configurations, waste forms.
- Diverse operational roles: district heating, desalination, hydrogen and electricity.
- Remote, distributed locations: access issues, lack of "unannounced" visit deterrence, cost-benefit issues.

Therefore, important safeguards features will be needed, such as unattended monitoring systems and remote data transmission; digital connectivity to coverage in remote areas (reliable, high bandwidth, secure); safeguards seals on factory-sealed and transportable cores; design verification, particularly under transnational supply arrangements; and, new safeguards approaches, including (potentially) customized IAEA or joint-use instrumentation. Other safeguards considerations are managing the efficient and effective implementation of safeguards for fleets of small, remotely distributed SMRs.

One of the important design features that IAEA pursues is safeguards by design that integrates safeguards considerations into the design process of new or modified facility, at any stage of the nuclear fuel cycle, from initial planning through design, construction, operation, waste management and decommissioning. This is a voluntary process that neither replaces a state's obligations for early provision of design information under its safeguards' agreement, nor introduces new safeguards requirements.

IAEA (Planning and Economic Studies Section, PES), CPR on the Economic Appraisal of SMRs – Mr Saied Dardour

Mr Dardour presented the preliminary results of the IAEA CRP on the economic appraisal of SMR projects. Within this project a generic methodology will be developed for assessing the relevance of the SMR option in a given context and for demonstrating the business case for SMRs. It is also planned to develop country cases and other case studies, focusing on SMR applications, and illustrating the implementation of the suggested methodology.

IAEA (Department of Nuclear Safety and Security, Division of Radiation, Transport and Waste Safety, NSRW), Transport Safety and Back End of SMR Fuel Cycle – Ms Shazia Fayyaz

Ms Fayyaz presented the IAEA perspective on transport safety for the back end of SMRs fuel cycle. It was concluded that SSR-6 which covers transport of radioactive material considering classification of material and packages remains applicable if cargo approach is considered for the back end of SMRs fuel cycle. However, the concept of transportable reactors is out of the scope of current IAEA transport safety framework.

2.2. SUMMARY OF INTERNATIONAL ORGANIZATION PRESENTATIONS (Prepared by Mr Surik Bznuni, Armenia)

EC/JRC, JRC Contribution to SMRs and the Back-End Fuel Cycle – Ms Concetta Fazio

Ms Fazio presented EC/JRC contribution to SMRs and relating back end of the fuel cycle. She presented the JRC mission and vision as well as the key objectives of the EURATOM framework programme 2021-2025. After, she introduced the SMRs in the European context and listed the main expectations and challenges for this new type of reactors.

The issues to be considered for the SMRs' waste management in terms of pre-disposal and disposal phases, are related to the different types of fuels, enrichment, burn-up, cladding materials and applied fuel cycle. To anticipate SMRs' waste management studies, the JRC performs investigations on spent nuclear fuel/waste analogues. The studies are aimed at providing data that would allow the confirmation of the compatibility with existing/planned waste management schemes. The investigations are oriented towards the pre-disposal and final disposal stages. The final disposal studies, which are relevant for the safety case, include corrosion experiments to correlate the irradiation history with the instant release fraction; the assessment of the long-term stability of the SNF in reducing/oxidizing conditions and addresses also the SNF heterogeneity. Studies related to the pre-disposal stage are aimed also at measuring the response of SNF to different mechanical loading conditions.

In conclusion, there is a growing interest in Europe towards SMRs and there are several SMR designs under consideration. Specific aspects that can possibly affect the back end of SMR fuel cycles needs to be identified and R&D should focus on these aspects through dedicated studies.

OECD/NEA, Update on OECD/NEA Activities Regarding the Back end of SMR – Ms Rebecca Tadesse

Ms Tadesse presented an update of OECD/NEA On-going Activities on the Back End of the Fuel Cycles for SMRs. She discussed results of the ad-hoc OECD/NEA Expert Group on Extended Storage and Transportation, highlighting that:

- There exists a wide range of specialized tools and analyses for certain areas of the fuel cycle (looking at optimized operation, optimized loading of final disposal canisters with respect to maximum heat per canisters, etc.)
- Clarity with respect to the end point of SNF storage is needed. Storage (even extended) is an interim stage of RW/SNF management, and it is necessary to identify the appropriate timescales and the purpose of RW/SNF storage.
- From the point of view of organizational framework, it is necessary to ensure that the extended storage does not lead to the appearance of a new legacy for next generation.

European Repository Development Organization (ERDO), The Potential Impacts of SMRs on Multinational Cooperation at the Back end of the Fuel Cycle – Mr Charles McCombie

Mr McCombie presented ERDO association's activities on analysis of the back-end options for SMRs. He stated that acceptance of nuclear is/has been strongly affected by disposal issues. Therefore, ERDO looks for multi-national cooperation in addressing challenges of the back end of the fuel cycle. He discussed the ongoing US DOE sponsored project on the potential impacts of SMRs on multinational cooperation at the back end of the fuel cycle.

Key messages of his presentation were:

- If the "waste disposal problem" is removed by a take-away offer, then non-nuclear countries might reconsider the nuclear option. New nuclear countries are more likely to order an SMR if the supplier takes back the entire module or the SNF,
- SMRs may enhance the "image" and the acceptability of nuclear power so that large NPPs also become more acceptable.
- Multiple SMR customers of the same design may cooperate on developing SNF conditioning and packaging approaches.
- Suppliers of SMRs – especially those with novel fuel cycles – may be interested in building multinational "user groups",
- Major established disposal programmes may see opportunities in accepting relatively modest amounts of SNF from new SMR countries,
- Suppliers of SMRs may exert pressure on their home countries to accept return of spent core modules or of SNF elements.

2.3. SUMMARY OF NATIONAL PRESENTATIONS (Prepared by Mr Andrea Salvatores, France; Mr David Hambley, UK; Ms Fatimah Al Momani, Jordan)

Armenia (NRSC), Safety Implications on the Back End of the Fuel Cycle for SMRs – Mr Surik Bznuni

Armenia operates a single nuclear power station and a dry storage facility based on the NUHOMS concept. According to the country's current strategic plan for energy sector development (for 2015 to 2036) a nuclear power unit necessarily must be part of the electricity generation installation structure. In this framework, activities are foreseen for second lifetime extension of the existing nuclear power unit to permit operation for an additional 10 years (from 2026 to 2036). Before 2036 a new nuclear power unit, as replacement capacity, must be commissioned. Additionally, in 2023 it is planned to extend the dry storage facility.

Concerning the reactor choice, currently three possible technological options could be realistic for Armenia: a mid-size PWR unit with about 600 MWe capacity or 2 small size PWR units with about 300 MWe capacity each or several SMRs. Regarding this last type of reactor, SMR designs consider the use of fuel with enrichment higher than 5% threshold. This enrichment could have significant implications on the back end of fuel cycle. Indeed, LWR fuel analysis were validated mainly based on experiments with enrichments less than 5%. Therefore, the validation of models and codes might be extended. New experiments involving both fresh and spent fuel assemblies with enrichments higher than 5% have to be carried out to support this validation. These considerations are not limited solely to neutronic core calculations but also to transport and storage.

These new fuels will have a strong impact on the design of the transportation cask because of criticality considerations. The limitation of the number of fuel assemblies and burnup credit could be used to tackle these issues. The residual decay heat arising from increased irradiation will also affect the storage. The thermomechanical properties should be addressed and re-evaluated by designers and vendors in terms of corrosion, hydrogen uptake, and volatile fission products in the spent fuel.

Uzbekistan (The State Committee of Industrial Safety of the Republic of Uzbekistan), Fuel Cycle Consideration for WWR-SM research reactor – Mr Boltabaev Azizbek

Uzbekistan has 6 nuclear facilities used for R&D. The research reactor fuel evolved by gradually lowering the uranium 235 content which results in an increase of the number of assemblies in the core. Initially the number of assemblies was 18 and increased to 20 and finally to 24 assemblies. Managing the storage of spent assemblies is therefore a key issue. Uzbekistan has changed its storage capacity, both for fresh and spent fuel. Storage capacity has been recovered during the last years by means of a number of recent fuel exports. The storage of all these fuels (fresh and spent) is accompanied by a physical protection system consistent with the management of these materials.

Egypt (EAEA), Direct Recycling of SMR Spent Fuel for Uranium Utilization Improvement and Reduction of High-Level Nuclear Waste – Mr Nader M. A. Mohamed

Due to of its small core volume, an SMR core has a higher neutron leakage than that of large-scale reactors. It follows that SNF discharged from SMRs will present higher residual content of fissile materials which would: (1) degrade the uranium utilization and (2) increase the high-level waste. Therefore, direct recycling of the SMR spent fuel in CANDU reactors, through for instance the DUPIC cycle (originally proposed in Republic of Korea), would improve the uranium utilization and reduce the high-level waste.

As a case study, direct recycling of the spent fuel of NuScale SMR was investigated. In this case study, NuScale SMR is loaded with fuel that has an average enrichment of 4.175% U-235 and discharges the spent fuel with average burnup of 40.4 GWd/t. Calculations using MCNPX computational code showed that recycling of the NuScale SMR spent fuel in CANDU-6 reactor would give additional burnup of 20 GWd/t, increasing the burnup in about 50%. Also, the high-level waste will be reduced by the same percentage i.e. 50%. Calculations of the evolution of the reactor cores provide clear demonstration elements of how to integrate SMRs in an efficient and optimized manner in a large reactor fleet, not only in terms of the production of electricity but also of their back-end management.

Slovenia (Slovenian Nuclear Safety Administration), Design Extension Conditions for Spent Fuel Storage at the PWR NPP KRŠKO – Mr Tomi Živko

Slovenia is the smallest nuclear country. The storage of spent fuel is a major subject for the sustainability of nuclear activities and two main factors had impacted its management during the last decades. On one hand, the Fukushima accident, which gave raise to new considerations regarding the safety of storage, and on the other hand, the extension of the operating life of the NPP, led to changes in the SNF storage options with the creation of dry storage technologies and the improvement of SNF pool safety, through the installation of a mobile cooling system (firefighter or river) and a dry storage design resistant to earthquakes and severe atmospheric events. The end of the construction of spent fuel dry storage is planned for 2022 and the filling should start in 2023. An important point of these evolutions is the fact that the specifications of the Slovenian regulations should in principle make it possible to receive the storage of SMR fuels – although some points would need to be validated. Once again, we see that the progression of nuclear power has an impact not only on the reactors but also on the various installations of the cycle.

Poland (INCT), The Process of Decarbonization of the Domestic Power Industry in Poland using SMR Reactors – Ms Agnieszka Miskiewicz

A comprehensive presentation of the Polish energy panorama highlighted the importance of the fossil component in its energy mix and its need to evolve towards de-carbonized energies. Poland does not have a nuclear power reactor but 6 LWR units are planned to start being built by 2033. In addition, low power HTGR reactors (200-350 MW) are considered for heat generation. This decision on HTGR would be consolidated by the construction of a small pilot unit of 10 MWth. This panorama should be completed by the evaluation of several SMR concepts. Work is underway to develop criteria for evaluating SMR suppliers individually as well as by a set of criteria bearing on a more global approach to address needs for a fleet of reactors.

Jordan (JAEA), Considerations and Perceptions for Nuclear Fuel Cycle Back End Related to the SMRs under Consideration in Jordan – Ms Fatmah Al Momani

Jordan, as many other countries, is facing a growing demand of energy. Additionally, there is a real need for a domestic reliable and affordable base load power. Available energy options are limited and have intrinsic limitations (durability, efficiency, environmental considerations, etc.). In this framework, nuclear energy is under consideration with two approaches at a different degree of maturity: large reactors (negotiations with vendors) or small power plants (technical and economic assessment). Concerning the SMR option, several factors are analyzed including integration in the current infrastructures, diversification of uses, safety, etc. In terms of the back end, after storage at reactor site, different technical options will be assessed, either considering the spent nuclear fuel as strategic resource that can be utilized through reprocessing (nationally or internationally) or declaring it as a radioactive waste to be disposed of directly in a national waste disposal facility. Until now no final decision on the spent nuclear fuel management option has been taken as it will be based on the selected reactor technology. The shortlisted SMRs (based on matrix evaluation criteria) are: a) HTR PM China/CNEC b) NuScale USA/NuScale Power and c) RITM Russia/Afrikantov OKBM. The management of the spent TRISO or oxide fuels is evaluated step by step including a potential reprocessing option outside Jordan for the RITM option.

France (CEA), Back End of the Fuel Cycle Considerations for Small Modular Reactors – Mr Andrea Salvatores

To reach carbon neutrality by 2050 to limit global warming, an energy transition has been initiated in France. Renewable and nuclear energies can play a significant role in a context of electrification of many uses. Nuclear energy development requires construction sites, financial commitments of several billion Eur, societal approval and its delivery is complex. Therefore, small nuclear reactors, which require lower financial commitments, with shorter construction times and with greater simplicity to operate should be part of the French energy strategy. In the frame of the investment plan « France 2030 », 500 MEur will be assigned to the development of the French SMR – Nuward and additionally, 500 MEur will be dedicated to proposals for new reactor concepts in the field of fission and fusion. The main objective is to create a new ecosystem for the nuclear sector. The collaboration of the French nuclear safety authority with the Finnish and Czech nuclear safety authorities for a joint preliminary review of the NUWARD™ reactor project is a good example of this new ecosystem. France has the main facilities needed for managing spent fuel. Evolutions/adaptations could be needed to accommodate new fuels coming from SMR concepts. A global vision of the nuclear fuel cycle is needed (starting materials and natural resources, life cycle, economy, storage, transportation, waste management).

France (Orano), Advanced Nuclear Reactors: What about the Back end? Focus on Treatment and Reprocessing/Recycling Aspects – Mr Renaud Liberge

The management of the back end of Advanced Reactors can be approached through their fuel types (Oxide/ceramic fuels with cladding, TRISO fuels, Metallic fuels, Liquid salt fuels) and fissile feature (LEU, LEU+, HALEU, HEU, mixed Uranium and plutonium, thorium). In the case of oxide fuels, (sintered pellet UO_2 or MOX fuel similar in design to the existing-LWR oxide fuel), they can benefit from a consolidated operating, manufacturing, recycling and irradiation experience. The situation of the TRISO fuel is a little bit different due to the intrinsic low density of the fissile material in the fuel and the complexity to access to it. So, a treatment of the spent TRISO fuel to remove/reduce graphite content would be needed for storage and for disposal. The pulsed currents could be a solution to separate the graphite component, maintaining the integrity of the TRISO particles. Metallic fuels are generally treated by pyro-processing and aqueous polishing processes. A treatment for the residual sodium could be needed for storage and disposal steps. Finally, liquid fuels coming from Molten Salt Reactors could be treated by pyro-processing or by integrating them in a treatment-recycling hydro-process plant. These considerations show that designing the back end of the fuel cycle from the beginning as a whole system is essential. When possible, closed fuel cycle offers many advantages from a sustainability point of view (waste minimization, preservation of resources, reuse of valuable materials, optimization of final disposal).

France (CEA), Molten Salt Reactor Technology – Mr Vincent Pascal

The operation of Molten Salt Reactors (MSRs) is far from the well-known operation of traditional solid fuel reactors (Light Water Reactors (LWRs), Sodium Fast Reactors (SFRs), …). MSRs have potential benefits as flexibility in terms of fuel isotopic enrichment, quick and efficient thermal feedback effects, a fuel loop without pressurization, natural convection capabilities, high efficiency of the energy conversion system, etc. MSR development roadmaps need to resolve key issues like the corrosion resistance of materials submitted to molten salts, the thermal load due to high temperature operation, the salt nuclear depletion and the fission products management, the handling of salt and the maintenance of components, etc. French spent fuel reprocessing is based on the closed cycle strategy with the idea that produced fissile actinides in LWRs can be reused and valorised, which induces enriched uranium savings.

In 2020 CEA and ORANO launched preliminary studies around fast MSR technology in the framework of a common R&D effort for transuranic actinides' management. Preliminary evaluations (at steady state) show a promising potential for the reduction of volume and long-term radiotoxicity of ultimate waste using MSRs as Pu+MA convertors, as a complementary service to Pu mono- and/or multi-recycling options. ISAC Project (CEA/CNRS/EDF/FRA/ORANO) aims to assess the potential of fast MSRs to enhance French nuclear material management strategy.

France (Orano), Integration of MSRs in LW-SMR Fleets to Close their Fuel Cycle and/or Manage Waste – Ms Isabelle Morlaes

Beside the standard options for the integration of Light Water Cooled SMRs in the current back end of the fuel cycle (i.e., direct disposal or multi-recycling of plutonium), a preliminary study has been performed to assess the potential of fast chloride MSRs in a symbiotic fleet of SMRs to "burn" Pu and MAs from the LWC-SMRs. Coupling the La Hague plant with fast MSRs converting actinides into fission products would add value to the standard LWRs spent fuel reprocessing activity, in terms of natural resources and reduction of volume and long-term radiotoxicity of generated wastes. Most of these process steps are already available in La Hague at industrial scale to achieve this « symbiotic » system. Using synergies with the industrial capabilities of La Hague can accelerate the development and deployment of such back end solutions for LWC-SMRs. It is recalled that the halide coming from the spent salt is also recycled to recover this valuable constituent and to minimize the load of the waste with this element.

Canada (MoltexEnergy), Application of a Graded Approach to the Concept of Fuel Recycling – Mr Olivier Gregoire

The Moltex Stable Salt Reactor-Wasteburner (SSR-W) and Waste to Stable Salt (WATSS) process is designed to deliver benefits as outlined in the earlier presentation on the value of MSFR systems with respect to utilisation of low-grade Pu containing fuels and transmutation of minor actinides. This presentation focused on addressing potential proliferation concerns associated with the WATTS process that is proposed for manufacturing fuel salt from spent fuel, which might arise because of the process being interpreted as being similar to reprocessing. The presentation highlighted the lack of authoritative definitions for the concepts of reprocessing and recycling and reported widely adopted wording for such concepts. It set out the barriers to proliferation arising from inherent characteristics of the WATTS process, which does not separate Pu, and is not suitable for the separation of Pu from other actinides and some lanthanides. During subsequent discussion it was noted that the recycling plant is foreseen to be associated to the SSR-W reactor developed by Moltex to form an overall package.

Finland (STUK and VTT), Finnish Perspectives on SMR Back End of the Fuel Cycle – Mr Ville Koskinen (STUK) and Mr Timothy Schatz (VTT)

The first part of the presentation covered the ongoing revision of Finnish energy legislation which will take SMRs into account. Although no SMR projects are underway in Finland, interest has been expressed in their deployment for distributed local heating applications (Combined Heat and Power (CHP)), with LWR- SMRs currently being preferred. Initial regulatory review has indicated that storage and transport unlikely to present a challenge for current licensing processes, however the deployment of SMRs nearer urban areas may not be readily acceptable. Any new entity wishing to dispose of spent fuel will need to enter into commercial discussions with POSIVA for use of the limited unallocated capacity in the current Deep Geological Facility (DGF) or initiate their own DGF programme. Fundamentally the disposal concept is robust, but optimization of canister designs will be needed for shorter fuel. A nuclear safety and waste management R&D programme for the period 2023-2028 has recently been agreed in which SMR related activities are encouraged. Initial technical assessments of spent fuel characteristics from a reactor designed for local heating applications identified a lower inventory, heat and radiation arising from a lower target burnup but higher criticality hazard compared to a notional off the shelf LWR-SMR. The differences were considered insufficient to invalidate the current KBS3 disposal concept. However, the lack of fuel characterization, operational and maintenance experience and operating data limited the depth of analysis that could be undertaken. For significant deployment of small district heating units, centralized facilities for spent fuel and radioactive waste management would be attractive, however issues of ownership and liabilities would have to be worked out. Research has been started to understand whether the public would be accepting of SMRs being sited and waste management operations being undertaken in urban areas, with some mixed results.

Sweden (Studsvik), The Anita Program and SMR Spent Fuel Management from the Swedish Perspective – Mr Kyle Jonson

ANITA is an academia-industry collaboration to achieve sustainable future to understand legal and technical issues to enable SMR deployment by the end of the decade. The programme will assess a wide range of legal and engineering aspects relevant to SMRs. Currently the spent fuel management levy in Sweden represents 25% of operating costs, i.e., a level that could affect competitiveness. Changes to fuel designs or characteristics must be approved by SKB, as SKB is responsible for storage and disposal of spent fuel in Sweden. The process is also applied to import of fuel for PIE. The extent and duration of the technical assessments reflect the degree of deviation from current technical options and must be backed by experimental data. Where required, any remediation steps need to be defined and liability agreed before acceptance. To underpin and support this process of acceptance, it needs for data from irradiated specimens through test irradiation capacity and hot cell infrastructure for characterization and data generation.

Canada (CNL), Challenges of Small Modular Reactor Used Fuel Management in Canada – Mr George Xu and Mr Blair Bromley

A broad range of fuel types and SMR concepts are being evaluated, with work being prioritized by Canadian utility preferences and vendors potentially wishing to site demonstration of FOAK reactors in Canada. For remote locations the aim is to have very long batch fuel cycles. With HALEU options, previously developed schemes for fuel refabrication and re-irradiation in CANDU pressure tube heavy water reactors (PT-HWRs) could become more attractive because of higher residual enrichment and fissile content. Spent fuel inventories being assessed are based on open fuel cycle as a baseline consistent with current SFM strategy and planned infrastructure, pending completion of reprocessing studies and governmental reprocessing policy making. The range of assessed SNF heat generation rates from different concepts is very large. Pre-disposal management may be similar to that for current CANDU fuels, with remediation or processing and immobilization potentially being required for some options. In tandem with fuel recycling in the long term, transmutation has been looked at in terms of blanket assemblies in thermal-spectrum reactors, as a theoretical exercise to demonstrate that it is feasible, without any expectation that this strategy would be part of a preferred option that is ultimately implemented.

USA (DoE), Overview of US DoE's Office of Spent Fuel and Waste Disposition Activities – Mr Jorge Narvaez, Ms Natalia Saraeva and Mr Stephen Kung

Activities of DoE cover integrated waste management, R&D on waste management and international collaboration. On integrated waste management the current focus is on development and deployment of a consent-based siting process for centralized interim storage of current LWR fuels. Learning from this would ultimately also support SMR implementation activities. Waste management R&D is being undertaken to evaluate management and disposal options and inform decision making for current and SMR fuels, for which a range of examples were given.

USA (PNNL), Progress on Considering the Back End of the Fuel Cycle for Small Modular Reactors – Mr Stuart Arm

The focus of the presentation was on systems that could be adapted or deployed in the US in the near term. In relation to example decay heat generation rates at a common cooling time of 10 years, it was noted that these can vary substantially depending on management options selected for some fuels, specific examples given for molten salt and HTGR fuels. Whilst national regulations relating to interim storage can conceptually be applied to SMRs, there are many details to be worked through to address all nuances and to develop the data and designs required for licensing of such systems. Transport regulations were similarly generally applicable but there are significant gaps in understanding off normal transport conditions for licensing. Conditioning and treatment could be required for hazard reductions, regulatory compliance, economic viability or as a precursor to processing, depending on fuel type.

Work was underway to assess the conditioning potentially needed to transport and store MSR fuel materials. Interpretation of some regulatory terms, such as 'damaged fuel', would require further work, examples of MSR and HTGR fuels were again cited as examples with different characteristics. In summary, work is underway to understand the potential implications of SMRs' SNF in current LWRs' SNF management, and their possible post-discharge management options for subsequent disposal, which fell to DOE to resolve. Overall, work to date had recommended closer regulator-vendor interaction to develop and evolve regulatory requirements for SMR fuels.

USA (SNL), Investigations into Back End of the Nuclear Fuel Cycle (BENFC) Issues for Advanced Reactor (AR) Fuels and Accident Tolerant Fuels (ATF) – Mr Ramon Pulido

This presentation summarized current work on spent fuels for current and future reactors, including ATF and novel fuels. Characteristics of fuels that need to be understood to support assessments of disposal impact and hence inform integrated waste strategy for the back end management of all prospective fuel types were identified. The identified characteristics are similar to the list shown earlier by Sweden. Preliminary work indicates that current approaches with engineering adaptions for different geometries are credits for ceramic fuels, but more substantial adaptions would be required for other fuels. Work is planned to examine ATFs and SMR fuels currently under irradiation testing once they reach full burnup. PIE work supporting back end activities is based on that developed for the High Burnup Extended Storage Demonstration project "sister rod" examinations.

USA (ANL), Evaluation of Advanced Reactor Spent Fuel Management Facility Deployment – Mr Milos Atz

This presentation showed results of work to map the key processes and milestones associated with delivering new spent fuel management infrastructure and the associated implementation risks. Key milestones included establishing responsibilities, siting, transport infrastructure, facility design, licensing and permitting, construction and commissioning. For each type of facility and each type of fuel, a qualitative assessment was made of the extent to which implementation would be more difficult than for current LWR fuels. This led to identify different challenges for different fuel types. The overall outcome led to identify commonality across many facilities and fuel types and identify recommendations for government activities for legal framework changes to facilitate deployment of required facilities.

USA (NEI), Opportunities to Optimize Small Modular Reactor (SMR) Used Nuclear Fuel Management in the United States – Mr Rod McCullum

The need to address new spent fuel management issues provides opportunities to drive improved solutions for fuel management. Over last few decades cost pressures have led to innovation in the development, deployment and optimization of dry fuel storage. Whilst the technical work required to develop and deploy management options for SMR fuels would require substantial innovation and development work, the industry has a good record and foundation for undertaking and delivering new solutions. Currently three suppliers – Holtec, Orano, and NAC International – are well positioned to meet US storage needs and continue to offer new and improved storage solutions in the quest to gain market share. They each possess highly sophisticated and proven analytical tools for evaluating every aspect of storage system performance (i.e., criticality, heat transfer, shielding, materials issues, etc.) that they can continue to refine and apply to the design of transportation and storage systems for SMR used fuels. There is a re-emergence of recycling as part of the US fuel cycle that will create opportunities to produce tailored waste forms designed with long-term storage, transportation, and disposal in mind. SMRs deployed along with recycling technologies have the potential to redefine the very nature of used nuclear fuel, both for that discharged from SMRs as well as much of the existing inventory.

Romania (Nuclear and Radioactive Waste Agency), Romania Strategy for Radioactive Waste and Spent Nuclear Fuel according with the Development of the Expending Nuclear Program – Ms Alice Mariana Dima

Currently, Romania has decided to use open-cycle nuclear fuel, considering spent nuclear fuel as high-level waste, which is to be permanently disposed of in a deep geological repository. The CERNAVODA NPP has two CANDU 6 reactors (each 700 MW), wet storage in the spent fuel bay for minimum 6 years of cooling and dry storage in the intermediate dry spent fuel storage facility (DICA) for 50 years. Romania also has Research Reactors: a 14MW TRIGA reactor and a VVER research reactor that was shut down in 1997. The National Strategy establishes two main solutions for the safe management of radioactive waste and spent nuclear fuel: Implementing a near surface repository for low and intermediate level, short lived waste (DFDSMA); and a Deep Geological Repository for long lived radioactive waste & spent nuclear fuel. The new nuclear installations planned in Romania are the Advanced Lead Fast Reactor European Demonstrator (ALFRED) and the Extreme Light Infrastructure-Nuclear Physics (ELI-NP). First SMR from Europe and NuScale SMR where a preliminary phase of engineering, and design studies are still underway to provide essential data for the development of Romania's first small modular reactor plant. As many other countries with relatively recent nuclear power programmes, the geological repository programme in Romania is at an early stage and takes into consideration all technical solutions for disposal of the SNF and HLW.

France (Orano), Challenges for Transport and Storage – Mr Brut Stephane

Interim storage and transportation are critical parts of the overall management of the front end and back end. In addition, licensed solutions must be available for the various fuel types to be transported. Anticipating the package solutions is key to optimized transport scenarios and should be integrated early in the reactor design phase. The national regulations based on the IAEA Safety Standards, and the radioactive material characteristics (radioactivity, fissile material) defines the type of package, the safety requirements and tests to be conducted. The design features for fissile material as assumption of water ingress inside the package shall be considered in the criticality analysis, unless the package is double barrier design. Package design for fresh fuel with high fissile content shall be considered as well as all its by-products from the manufacturing chain. For example, UF_6 transport with enrichment higher than 5%. The simple barrier design with high fissile content subcriticality may reduce the payload capacity. Double barrier design enhanced reduction of package numbers and transport cost and the complexity of the design and additional operations. For spent fuel transport and storage, heavy cask due to shielding requirements with high density materials, large cask with impact limiters for transport, and compatibility with the loading facility process should be considered. Therefore, the existing solutions like TN-EAGLE® and NUHOMS EOS® and systems, licensed for LWR fuel, can be adapted/modified for such needs.

UK (Nuclear Transport Solutions), Transport Considerations for SMR Fuel Cycle and TNPPs – Mr George Burnett

The UK is planning to seek approval of one new reactor per year until 2030. UK SMR is expected early 2030s and potentially more licensed sites across UK as UK SMR is looking to deploy on previously licensed sites. In the IAEA Booklet on Advances in Small Modular Reactor Technology Developments, it can be identified examples of nuclear fuel transport experiences such as Energy Well, MicroURANUS, ELENA and eVinci. Transport Security Approach for SMR Applicability implies: Categorise material (type, form and quantity) adopting a graded approach; Sabotage considerations (especially for back end); Incorporate Design Basis Threat (DBT) / Threat Assessment; Implement defence in depth and remote transport and siting. The Transport Gaps can be summarized as: Transport safety substantiation of fuel characteristics (SSR-6 Normal Conditions of Transport and Accident Conditions of Transport); Data availability for Package Design Safety Report requirements and Package availability unknown; and Inherent security characteristics (theft vs sabotage). Some insights on safety and security aspects for transportable nuclear power plants were highlighted.

Argentina (CNEA), Back End the Fuel Cycle Considerations for CAREM the Argentinian Small Modular Reactor – Ms Laura Kniznik

CAREM-25 design is based on an integrated LWR, using enriched uranium as fuel. It is an indirect cycle reactor conceptually simple, which offers a high safety level. CAREM fuel elements are hexagonal section with 127 rods, of which 108 are fuel rods and 18 are guide tubes for absorbing elements and one is an instrumentation tube. Reactor core has 61 fuel elements. Annual refuelling will comprehend the whole core. Qualification of enriched uranium fuel pellets fabrication process began towards the end of

2018. The foreseen options for managing spent fuel for CAREM are similar to the others NPPs in Argentina: wet storage during the necessary period to allow sufficient decay of the fission products and later interim dry storage on the reactor site. Radioactive waste (RW) to be generated in normal conditions in CAREM-25 will be low or intermediate level RW. CAREM-25 design provides long interim storage for RW within the CAREM site.

UK (NNL), Managing Fuel from SMRs: UK Framework and HTGR Gap Analysis – Mr David Hambley

The UK remains committed to nuclear power as a key technology for meeting net zero goals by 2050. New large LWRs are under construction and planned to replace existing reactors that are expected to cease generation by the end of this decade. The UK is supporting development of a range of SMR and advanced nuclear technologies, with anticipated implementation starting in the early 2030s. The UK is now operating an open fuel cycle. Reprocessing remains an option if economically and environmentally attractive. Management of current spent fuels is mature and consistent with national strategy. The siting process for a deep geological disposal facility is underway with four candidate community partnerships having been established. The UK regulation provides mechanisms that ensure appropriate consideration of the whole fuel cycle through development, licensing, operation and modification of reactors and fuels.

For the HTGR, the technological options for spent fuel management are non-dismantling (co-disposal of fuel components and graphite materials) and dismantling (core components separation). Current priorities are associated with determining the conditions under which several degradation phenomena may be of concern, principally: longevity of TRISO containment layers in groundwaters, oxidation of TRISO containment layers and fuel graphite components, effects of He pressurisation on the increase of failed fuel proportion during timescales relevant for long-term storage and disposal, and the extent of fission product migration into and through TRISO containment layers.

Poland (INCT), TRISO Fuel Management Depending on the Choice of the Fuel Cycle Research Currently Conducted at INCT, Warsaw, Poland – Ms Katarzyna Kiegiel

Poland plans to have nuclear power from about 2033 including small modular reactors based on high-temperature reactor technology. There is a planned construction of the first HTR reactor with a capacity of approximately 150 - 300 MW before 2031. Open and closed fuel cycle options are being considered for TRISO spent fuel management: an open fuel cycle is recommended now, although a closed fuel cycle may be considered in the future. At present, the temporary on-site storage of spent nuclear fuel from Polish nuclear reactors is recommended. Next, it can be transferred to the deep disposal facility, when it will be available, or reprocessed. High-level waste from reprocessing will be disposed of in this deep repository, too. INCT is involved in European Projects on radioactive waste management and has experience in studies on the safe management of radioactive waste from the fuel cycle. The numerous studies being carried out concentrate on the development of the procedures suitable for the HTR waste management. It seems that improved extraction methods based on the currently employed ones for reprocessing spent nuclear fuel will be suitable for managing spent fuel from Gen-IV reactors.

Japan (JAEA), Fuel Cycle Scenarios and Back End Technologies of HTGR in Japan – Mr Yuji Fukaya

JAEA introduced the status of R&D on back end technologies for HTGR fuels and technological subjects to improve the specifications for some fuel cycle scenarios. Japan had developed reprocessing technologies for LWR spent fuels based on French technologies. R&D on back end technologies for HTGR spent fuels is necessary for demonstration at industrial level. HTGR technologies had been developed with assuming reprocessing in Japan. Head-end process of reprocessing for HTGRs had been completed, and applicability to Rokkasho Reprocessing Plant (RRP) had been confirmed. The disposal technologies for vitrified waste apply to HTGRs, and feasibility for direct disposal of HTGR spent fuels had been also confirmed.

To improve specifications of fuel cycle options a near field model for graphite waste dose evaluation should be developed. The waste may be disposed of more easily from shallow-ground pit disposal to shallow-ground trench disposal. The recovery ratio of reprocessing with HTGR head-end process should be confirmed to achieve potential toxicity reduction for multi-recycling option.

China (INET), Deconsolidation of HTR-10 Irradiated Fuels & Measurement of Burnup for SFE Storage – Ms Xiaotong Chen

The commercialization of HTGRs in China highlights the storage challenge of spherical fuel elements (SFEs). The burnup measurement of SFE is an important issue. Three SFEs with low to medium burnup were selected and measured using destructive and non-destructive methods. Gamma and mass spectrometry were applied, and an electrochemical deconsolidation process was conducted to obtain TRISO fuel particles from specific regions. The uniformity of burnup in each SFE was also studied simultaneously by a mass spectrometry method. Gamma spectrum of three SFEs (P1, P2, P3) were first collected by an online burnup measurement system (BUMS) before unloaded from HTR-10 and transferred to the hot cell, where provided a much lower radiation background and longer live time than at the reactor. Radioactivity of caesium fission product was sophisticatedly measured. The main radionuclides like U-235, U-238, Cs-137 and Nd-148 were measured by radiometric and mass spectrometric methods. The fractional U-235 burnup was used to determine the burnup distribution, which proved that in each SFE, the burnup is relatively uniform. The measured burnup using gamma spectrometry by Cs-137 compared well with the one using mass spectrometry by uranium nuclides.

2.4. SUMMARY OF BREAK OUT SESSIONS (Prepared by Mr Jorge Narvaez, USA; Mr Timothy Schatz, Finland; Mr David Hambley, UK; Mr Andrew Worrall, USA)

Three breakout sessions were conducted to identify and discuss gaps/challenges/opportunities for implementing back end of the fuel cycle strategies for different SMR Technologies (LWRs, HTGRs, and Advanced Reactors including MSRs) as well as to discuss integration of different SMRs' fuel cycles with the ones already implemented for the current fleet of LWRs, focusing on the management of spent fuel.

2.4.1. Light Water Reactor (LWR) SMR designs

Fuel Type
There is uncertainty related to accident tolerant fuel (ATF) and High-Assay Low-Enriched Uranium (HALEU) fuel availability.

Fuel Data
It is important to characterize the spent nuclear fuel (SNF) that will be produced from this type of SMRs. This data affects transportation-related activities.

Transportation
Can existing cask designs be used to transport SNF from these SMRs, or it will be needed to design and license new casks for this specific purpose?

SMRs and their associated SNF and other waste forms may likely need to be transported back to their countries or points of origin. International land and maritime considerations must be taken into account to properly plan for the future transportation of SMRs and associated waste.

Decommissioning

Reactor decommissioning should be considered from the early stages of the design phase. This presents a challenge as well as an opportunity to engage communities in decommissioning-related activities.

Reprocessing
For LWR-SMRs that are expected to use HALEU fuel, reprocessing is likely to be a viable option.

Disposal
There is an opportunity to engage with nuclear embarking countries on the feasibility of using deep borehole disposal (DBD) as an alternative for spent nuclear fuel disposal.

Fuel Cycle Back End
There is an opportunity to encourage SMR and Advanced Reactor vendors to collaborate with Member States on how to successfully navigate the back end of the fuel cycle.

2.4.2. High Temperature Gas-Cooled Reactor (HTGR) SMR designs

Fuel Type
HTGRs use TRISO fuel that is typically fabricated into one of two forms: spherical pebbles or cylindrical blocks.

Choosing one option versus the other will likely come down to the country preference on refuelling type (online for pebbles and shutdown for blocks) and availability of the containers that will contain the irradiated waste forms.

Damaged Fuel
There is a need to characterize and define what “damaged fuel” looks like for TRISO fuel.

A potential challenge deals with the identification of damaged fuel during normal operation and the mechanisms needed to remove and manage the failed fuel. Is damaged fuel characterization done at the TRISO particle level, at the encapsulation level, or both?

Fuel Data
Data is needed to support the characterization of the fuel and the expected waste forms. This will likely help expedite the licensing process. It is also important to obtain criticality data as the TRISO particles are likely to be fabricated using HALEU fuel.

Transportation
It is important to account for accident scenarios during the transportation of TRISO spent fuel and associated wastes.

Storage
There are decades-long experience in air storage of TRISO spent fuel. In contrast, there is little to no experience in wet storage; thus, wet storage is not considered a viable option for TRISO spent fuel.

Reprocessing
Reprocessing of TRISO fuel is thought to be possible and only small-scale research has been conducted to date. Nevertheless, any processes will likely need to plan for how to best deal with the release of ^{14}C. The cost-effectiveness of reprocessing should also be accounted for when determining its feasibility. One key challenge is determining whether the reprocessed fuel can be recycled into fresh fuel for another reactor. Finding reprocessing alternatives without chemical disposal will likely be advantageous.

Disposal
TRISO spent fuels from several experimental reactors are currently being used to investigate disposal alternatives. However, more research and development are needed to conduct direct disposal of TRISO spent fuel. The consensus is that TRISO fuel is thought to be disposable after irradiation.

There is a need to identify the infrastructure framework (primarily for transportation) required for potential future international disposal.

Energy Mix
There is the potential for the integration of HTGR SMRs with hydrogen production or process heat. One key challenge is to determine the back end factors that could make this integration possible.

Safeguards
Some countries consider that HTGRs are an unattractive option to be deployed due to the material accountancy issues that arise when dealing with hundreds or thousands of pebbles required during reactor normal operation. This is a big challenge from safeguards perspective as TRISO fuel and associated waste forms could be diverted due to their relatively small size.

2.4.3. Advanced Reactors and Molten Salt Reactor (MSR) SMR designs

Fuel Type
Most advanced reactor designs include non-LWR fuel types. Some representative fuels are metallic, oxide, nitride/carbide, TRISO, molten salt, etc.

To understand the SNF, it is very important to first characterize the fresh fuel types proposed from the reactor vendors.

The fresh/SNF can be characterized by some of the following factors: chemical and physical properties, isotopic composition, neutron and gamma spectra, heat, burnup, cooling time, corrosion products, etc.

However, there are several challenges and gaps due to the diverse set of fuel types.

- To understand each fuel type, it is necessary to have cooperation from the vendors. This could be challenging due to intellectual property considerations.
- There is a need to create and maintain databases that could help researchers simulate the operation of these reactors. This could help to inform back end activities such as storage, transportation, and disposal.

SNF “Take Back” Option
The option of “take back” is very important and likely poses several challenges. This option occurs when a vendor or country agrees to take back the SNF or parts of the reactor (entire reactor vessel for microreactors) from other nations after reactor shutdown.

International agreements regarding SNF take back should be considered and put in place in anticipation of SMR and microreactor deployment.

Transportation and Storage
Packages that can accommodate the different fuel forms need to be designed and qualified.
One key challenge is to determine if one type of package can accommodate different fuel forms.

For molten salt reactors, an important challenge is determining if the SNF from these reactors will be in a solid or liquid form. It is important to identify if the expected form will remain the same under postulated accident conditions.

2.5. SUMMARY OF GENERAL DISCUSSIONS (Prepared by Jorge Narvaez, USA)

Safeguards
A discussion on how to work with the vendors about making their designs proliferation resistant took place.

Some general insights were provided by the IAEA Safeguards staff:

- Proliferation resistance is analysed from the preliminary design.
- Guidelines are in place to ensure that nuclear material that enters a facility is located where it is supposed to be and the design of a facility will not produce other unapproved materials.
- Several technical scenarios need to be considered. For example, a scenario in which a reactor operator or Member State use a facility to divert or produce other material. The more scenarios, the more complex the safeguards approach becomes.
- The more proliferation resistant a facility is designed; the less safeguards will be introduced for that facility.
- Regarding encapsulated or sealed reactor modules, there is no current set of safeguard activities required for verification. However, any activities need to be country-specific and need to be built around the vendor design. The use of cameras is considered for places where human verification is not possible.
- It is still unknown at this time if the Comprehensive Safeguards Agreement (CSA) needs to be amended to allow for the deployment of SMRs.

Other Topics

Fuel characterization is needed to anticipate what to do with the SNF. In Switzerland, a decommissioning plan is required prior to the operation of any nuclear power plant.

There was a proposal to review the definitions of reprocessing and recycling in the next revision of the "IAEA Safeguards Glossary".

Several participants expressed interest in the addition of the terms "social acceptance", and "public engagement" when involving members of the public in the activities related to the back end of the fuel cycle.

Coordinated Research Projects (CRP)

Here are some ideas of projects that some of the meeting participants expressed interest in seeing explored:

- Characterization of the fuel, spent nuclear fuel, and other waste forms associated with the operation of advanced reactors and SMRs.
  - This is something that could be done in parallel with the IAEA SMR Booklet.
  - It could be added to the current IAEA ARIS database as additional information on the back end of the fuel cycle from different SMR designs.
- Several participants expressed interest in the infrastructure needed to deploy advanced reactors and SMRs, and the cost analysis associated with this.
  - The "human infrastructure" needed to license and operate these facilities could also be considered. The number of jobs and the career types need to be identified as well.
- It is important to think about the transportation security for these types of reactors as well as for the regulations needed to transport HALEU fuel.
- Develop a simulation tool for advanced reactor fuel cycles:
  - The current IAEA simulation tool, the Nuclear Fuel Cycle Simulation System (NFCSS), is currently only capable of simulating thermal reactors as PWRS, BWRs, PHWRs, RMBKs, AGRs, GCRs, WWERs (UOX, MOX and ThOX fuel cycles). However, work is in progress to simulate advanced reactor fuel cycles.
  - New modules will be added to the simulation tool to address the footprint for disposal of advanced reactor fuel cycles.

2.6. CLOSSING REMARKS FROM THE CHAIRPERSON (Ms Cecile Evans, France)

For countries embarking or willing to embark with SMR, whether they are nuclear countries or newcomers, understanding implications of the spent fuel management program that would need to be undertaken is important to make informed decision on the specificities of different SMR technologies and on the fuel cycle options.

For various technologies/families of technologies, describing activities to be developed and implemented to manage spent fuel up to the disposal of HLW will enable to:

- Identify the various steps to be undertaken, their timeline and duration.
- List the data required to develop the various fuel cycle options, to predesign the back end program based on collected data on mass flows of materials and wastes; isotopic, chemical form, impurities, waste forms and their compatibility with disposal; building on from existing knowledge/boundaries conditions acquired so far and enabling sharing of information.
- Identify the data to be collected from irradiated fuel and their use in designing systems for licensing.
- Identify the gaps with existing practices/technologies/infrastructures developed for existing systems and the specific characteristics associated to SMR deployment as well as the opportunities to develop new technologies to fill the gaps.
- Identify which infrastructures, including their size, would need to be developed, whether they would be locally implemented or based on existing industry solutions/services, including cost elements.

This would require establishing specific roadmaps of activities to be developed per technology, identifying what can be derived from existing practices, optimized, adapted, or fully developed considering the lack of data, gaps with existing knowledge, and defining required additional data and the way to acquire them.

This would allow to compare various reactor technology systems, comparing fuel cycle options to identify/quantify the effort required to implement a spent fuel management strategy in terms of nuclear facilities, technology developments, types of nuclear materials involved, generated radioactive waste forms and other infrastructures needed such as human resources, regulatory framework, financing, etc. In addition, specific emphasis should be given to the need to develop/reach public engagement.

This work will allow to identify and highlight key parameters for designing the back end program of the different fuel cycle options associated with the different SMR technologies.

These roadmaps could be developed by the IAEA in the framework of a Coordinated Research Project (CRP) with the main objectives of:

- Identifying viable nuclear fuel cycle options for the different SMR technologies.
- Establishing generic key parameters that would then allow a country to develop from that tool their analysis incorporating their specific context.
- Identifying common technologies/similarities for various reactor types and/or significant differences.

Thus, there would be merits in having one CRP addressing the back end of various SMR technologies, to ensure that synergies and cross-cutting issues will be identified.

ANNEX I

TECHNICAL MEETING AGENDA

Tuesday, 20 September 2022			
9:30-9:45	1.	Welcome Address – Dir NEFW – SH NFCMS	Olena Mykolaichuk (IAEA) Clément Hill (IAEA)
9:45-10:05	2.	- Opening remarks Scientific Secretary - Overall Objectives of the Technical Meeting - Participating Organizations from Member States - Chairperson of the TM and Adoption of the Agenda	Amparo González (NFCMS, IAEA)
IAEA Presentations			
10:05-10:25	3.	SMRs Booklet	Hadid Subki (NPTDS, IAEA)
10:25-10:45	4.	Agency-wide Platform on SMRs and Their Applications	Stefano Monti (NPTDS, IAEA)
10:45-11:15 Coffee Break			
11:35-11:55	5.	IAEA On-going Activities on Spent Fuel Management	Amparo González (NFCMS, IAEA)
11:55-12:15	6.	Information on the IAEA TM on Back End Opportunities and Challenges for Spent e-ATFs Management (June 2022)	David Hambley (NNL, UK)
12:15-13:45 Lunch Break			
13:45-14:15	7.	Consideration of Non-Water Cooled Reactors and SMRs in the IAEA Safety Standards	Paula Calle (NSNI, IAEA)
14:15-14:35	8.	Security Considerations for Back-end of Nuclear Fuel Cycle for SMRs	Tariq Majeed (NSNS, IAEA)
14:35-14:55	9.	Safeguards Considerations for SMR Fuel Cycles	Kerrin Swan (SGCP, IAEA)
14:55-15:25	10.	CRP on the Economic Appraisal of SMRs	Saied Dardour (PES, IAEA)
15:25-15:55 Coffee Break			
15:55-16:15	11.	Transport Safety and Back End of SMR Fuel Cycle	Shazia Fayyaz (NSRW, IAEA)
International Perspectives			
16:15-16:35	12.	Update on EC/JRC On-going Activities on the Backend of the Fuel Cycles for SMRs	Concetta Fazio, EC/JRC (20’)
16:35-16:55	13.	Update on OECD/NEA On-going Activities on the Backend of the Fuel Cycles for SMRs	Rebecca Tadesse (OECD/NEA) (20’)
16:55-17:15	14.	ERDO Association	Charles McCombie (ERDO) (20’)
17:15-17:30	15.	Wrap up of the day	Chairperson
Adjourn 17:30h			
Wednesday, 21 September 2022			
Member State Presentations			
9:20-9:35	16.	Safety Implications on the Back End of the Fuel Cycle for SMRs	Surik Bznuni (Armenia) (15’)
9:35-9:45	17.	Fuel Cycle Considerations for WWR-SM Research Reactor	Azizbek Boltabaev (Uzbekistan) (10’)
9:45-9:55	18.	Direct Recycling of SMR Spent Fuel for Uranium Utilization Improvement and Reduction of High Level Nuclear Waste	Nader M.A Mohamed (Egypt) (10’)

9:55-10:05	19.	Design Extension Conditions for Spent Fuel Storage at the PWR NPP Krško	Tomi Živko, (Slovenia) (10')
10:05-10:15	20.	The process of decarbonization of the domestic power industry in Poland using SMR reactors - issues related to spent fuel as one of the parameters determining the choice of technology	Agnieszka Miskiewicz (Poland) (10')
10:15-10:25	21.	Considerations and Perceptions for Nuclear Fuel Cycle Back End Related to the SMRs under Consideration in Jordan	Fatmah Al Momani (Jordan) (10')
10:25-10:55 Coffee Break			
10:55-11:05	22.	Back End of the Fuel Cycle Considerations for Small Modular Reactors	Andrea Salvatores (CEA, France) (10')
11:05-11:20	23.	Advanced nuclear reactors: what about the back end? With a focus on reprocessing/recycling or treatment of various fuel types	Liberge Renaud (Orano, France) (15')
11:20-11:35	24.	Molten Salt Reactor Technology Opportunities of molten salt fuel for actinides management	Vincent Pascal (Orano, France) (15')
11:35-11:50	25.	Integration of MSRs in LW-SMR fleets to close their fuel cycle and/or manage waste	Isabelle Morlaes (Orano, France) (15')
11:50-12:05	26.	Application of a graded approach to the concept of fuel recycling	Olivier Gregoire (MoltexEnergy, Canada) (15')
12:05-13:20 Lunch Break			
13:20-13:45	27.	Finnish Perspectives on SMR Back End of the Fuel Cycle	Ville Koskinen (STUK, Finland) Timothy Schatz (VTT, Finland) (25')
13:45-14:05	28.	~~Managing Fuel from SMRs: UK Framework and HTGR Gap Analysis~~ *(Moved to Thursday 22)*	~~NNL, UK (20')~~
14:05-14:15	29.	~~TRISO Fuel Management Depending on the Choice of the Fuel Cycle - research currently conducted at INCT in Poland~~ *(Moved to Thursday 22)*	~~Katarzyna Kiegiel, (Poland) (10')~~
14:15-14:35	30.	~~Fuel Cycle Scenarios and Back-End Technologies of HTGR in Japan~~ *(Moved to Thursday 22)*	~~JAEA, Japan (20')~~
14:35-14:50	31.	~~Deconsolidation of HTR-10 Irradiated Fuels & Measurement of Burnup for SFE Storage~~ *(Moved to Thursday 22)*	~~Xiaotong Chen (China) (15')~~
14:50-15:15 Coffee Break			
15:15-15:35	32.	The Anita Program and SMR Spent Fuel Management from the Swedish Perspective	Kyle Johnson (Sweden) (20')
15:35-15:55	33.	Challenges of Small Modular Reactor Used Fuel Management in Canada	George Xu, Blair P. Bromley (CNL, Canada) (20')
15:55-16:15	34.	Overview of the U.S. DOE's Office of Spent Fuel and Waste Disposition Activities	Jorge Narvaez, Natalia Saraeza, Stephen Kung (DoE, USA) (20')
16:15-16:30	35.	Progress on Considering the Back End of the Fuel Cycle for Small Modular Reactors	Stuart Arm (PNNL, USA) (15')
16:30-16:45	36.	Investigations into Back End of the Nuclear Fuel Cycle (BENFC) Issues for Advanced Reactor (AR) Fuels and Accident Tolerant Fuels (ATF)	Ramon Pulido (SNL, USA) (15')
16:45-17:00	37.	Evaluation of Advanced Reactor Spent Fuel Management Facility Deployment	Milos Atz (ANL, USA) (15')
17:00-17:15	38.	Opportunities to Optimize Small Modular Reactor (SMR) Used Nuclear Fuel Management in the United States	Rod McCullum (NEI, USA) (15')
17:15-17:30	39.	~~Back End of the Fuel Cycle Considerations for the CAREM - the Argentinian Small Modular Reactor~~ *(Moved to Thursday 22)*	~~CNEA, Argentina (15')~~

17:30-17:40	40.	Wrap up for the day	
Adjourn 17:40			

Thursday, 22 September 2022

Member State Presentations			
9:15-9:35	41.	Romanian strategy on safe management of SNF and RW, including the new projects SMR and Generation IV	Alice Dima (ANDR, Romania) (20’)
9:35-9:50	42.	Advanced nuclear reactors: what about the back end? Focus on spent fuel storage and transportation for various fuel types	Stephane Brut (France, Orano) (15’)
9:50-10:10	43.	Transport for Small Modular Reactor Back End Fuel Cycle	George Burnett (Nuclear Transport Solutions, UK) (20’)
10:10-10:25	44.	Back End of the Fuel Cycle Considerations for the CAREM - the Argentinian Small Modular Reactor	Laura Kniznik (CNEA, Argentina) (15’)
10:25-10:55 Coffee Break			
10:55-11:15	45.	Managing Fuel from SMRs: UK Framework and HTGR Gap Analysis	David Hambley (NNL, UK) (20’)
11:15-11:25	46.	TRISO Fuel Management Depending on the Choice of the Fuel Cycle - research currently conducted at INCT in Poland	Katarzyna Kiegiel, (ICHTJ, Poland) (10’)
11:25-11:45	47.	Fuel Cycle Scenarios and Back-End Technologies of HTGR in Japan	Yuji Fukaya, (JAEA, Japan) (20’)
11:45-12:00	48.	Deconsolidation of HTR-10 Irradiated Fuels & Measurement of Burnup for SFE Storage	Xiaotong Chen (INET, China) (15’)
12:00-13:00 Lunch Break			
13:00-13:15	49.	Break Out Session Objectives and Materials	Amparo González (NFCMS, IAEA)
Break Out Sessions *(Please, go to your assigned Room)* M0E13, M0E15, M0E16			
13:25-15:00	50.	3 Working Parallel Sessions per SMR Technology (LWRs, HTGRs, ARs+MSRs) to identify and discuss gaps/challenges/opportunities for implementing Back End of the Fuel Cycle of SMR Technologies	All
15:00-15:30 Coffee Break (All back to M7 or main on-line session)			
15:30-17:30	51.	Summary of discussions from each per Working Team (15’ each) on: - LWRs - HTGRs - ARs + MSRs General discussion on cross-cutting challenges/issues/opportunities	All
Adjourn 17:30			

Friday, 23 September 2022

General Discussion on TM Findings and Member States’ Recommendations			
9:15-10:45	52.	Review of discussions during TM and Break Out Sessions on gaps/challenges/opportunities for implementing Back End of the Fuel Cycle of SMR Technologies General Discussion on cross-cutting challenges/issues/opportunities	Chairperson to lead All
10:45-11:15 Coffee Break			
Discussion on potential future IAEA and TM Conclusions			
11:15-13:00	53.	Discussion on potential future IAEA activities, collaborations and path to move forward	Chairperson to lead All
Adjourn 13:00			

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