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OECD Nuclear Energy Agency (NEA) Scientific Activities on Advanced Fuel Cycles

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The OECD Nuclear Energy Agency (NEA) advances the development of advanced nuclear fuel cycles through its Working Party on Scientific Issues of Advanced Fuel Cycles (WPFC). Comprised of four expert groups, the WPFC focuses on fuel cycle scenarios, fuel recycling, innovative fuels, and reactor coolant technology. These efforts address sustainability, safety, non-proliferation, and economic challenges associated with advanced fuel cycles and technologies. Key initiatives include benchmarking studies, data preservation, and support of Gen-IV reactor technologies. Recent WPFC activities include workshops and publications on Molten Salt Reactors (MSRs) fuel cycles, partitioning and transmutation (P&T) techniques, and assessment of advanced fuel properties. Expert groups also explore separation technologies, innovative fuel types, coolant impacts on reactor components, and advanced fuel cycle scenarios. These initiatives support global efforts, such as the commitment by over 20 countries at COP28 to triple nuclear capacity, ensuring efficient resource use and waste management. The WPFC's work underscores the role of advanced fuel cycles in meeting future energy demands.

KEYWORDS: advanced fuel cycle scenarios, used fuel recycling, fuel cycle closure, innovative fuel elements, innovative coolants and components, international co-operation

I. Introduction

Advancing research and innovation in the fuel cycle field is crucial for maintaining and enhancing the performance and safety of nuclear activities, in addition to improving resource utilisation. Expertise in fuel cycle physics and chemistry is also fundamental for developing and deploying advanced reactor systems, which are currently receiving considerable attention as part of the commitment towards incorporating nuclear energy into the broader energy transition. This commitment has been highlighted by the joint declaration made at COP28 by 22 countries to triple their nuclear capacity.

The OECD Nuclear Energy Agency (NEA) develops and disseminates scientific and technical expertise in the field of advanced fuel cycles, with its Working Party on Scientific Issues of Advanced Fuel Cycles (WPFC), operating under the auspices of the NEA Nuclear Science Committee (NSC).

Established in 2004, the WPFC underwent restructuring in 2020, with a revised objective placing increased importance on the back end of nuclear fuel-cycles and on advanced fuel cycles of innovative systems. The working party is now organised with four expert groups as follows:

- Expert group on Advanced Fuel Cycle Scenarios (EGAFCS).
- Expert group of Fuel Recycling and Waste Technology (EGFRW).
- Expert Group on Innovative Fuel Elements (EGIFE).
- Expert group on Reactor Coolant/Component Technology (EGCoCoT).

These Expert Groups were established through a consensus process within the NSC. Each group is composed of international experts from member organisations, research institutions, and industry representatives. The Expert Group chairs are elected by the group members based on expertise, and initiatives within the groups are guided by defined mandates and work programmes aligned with WPFC's strategic objectives.

II. WPFC Objectives and Structure

The WPFC's objective is to support the industrialisation of advanced fuel cycle. This involves reducing uncertainty through benchmarking and data sharing, and increasing safety through material, components, and design optimisation in both normal and off-normal conditions. Additionally, the WPFC facilitates data preservation by developing and maintaining databases, while also offering recommendations to the global scientific community.

The tasks of the Expert Groups within the WPFC includes analyses of different types of Generation IV reactors, with innovative fuel management options such as, hydro-/pyro-reprocessing, plutonium burning and/or multi-recycling, and

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minor actinide transmutation. These topics were explored and discussed during previous Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation (IEMPT), such as the 15th IEMPT,[1] and the 16th IEMPT which was hosted by the NEA on October 2023.

Collaboration between the WPFC Expert Groups is essential for integrating insights from different aspects of the fuel cycle. For examples, key findings from the EGFRW regarding recycling technologies are used as input assumptions for fuel cycle scenario modelling by the EGAFCS. Additionally, WPFC collaborates with other divisions within the NEA, such as the Working Party on Nuclear Energy Economics (WPNE), which contributes economic assessments for various parts of the fuel cycle. These interactions enhance the robustness of WPFC analyses and facilitate comprehensive recommendations.

The deliverables from the WPFC activities, including benchmarking reports, handbooks, and state-of-the-art studies, serve as reference materials for nuclear industry stakeholders. For example, the 2015 Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies[2] is used extensively by reactor designers, academia and regulators.

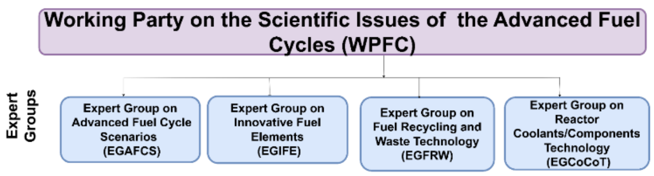

Fig. 1 Structure of the WPFC

III. Expert Group Objectives and Activities

1. Expert Group on Advanced Fuel Cycle Scenarios (EGAFCS)

The EGAFCS studies the needs associated with the transition from current to future advanced nuclear fuel cycles. This is supported by the group's objectives, which are to assemble, organise and understand the scientific issues of advanced fuel cycles to support emerging nuclear fuel cycle technologies, and provide a framework for assessing specific national needs related to implementation of advanced fuel cycles.

(1) Past Activities

The Expert Group on Advanced Fuel Cycle Scenarios (EGAFCS) has conducted a range of activities leading to reports, categorised into benchmarking, sustainability transition studies, and uncertainty analysis.

Benchmarking studies:

Two critical benchmarking exercises were conducted to evaluate computational models:

1. Benchmark Study on Nuclear Fuel Cycle Transition Scenarios Analysis Codes[3] compared the codes COSI, VISION, FAMILY21, DESAE, and EVOLCODE, examining their capabilities in modeling depletion and transition scenarios. Key outputs included insights into material flows, enrichment needs, and spent fuel inventories for scenarios like open cycles, limited plutonium recycling, and advanced fast reactor deployments.

2. Benchmark on Dose Rate Calculations for Irradiated Assembly[4] benchmarked multiple computational codes against experimental data to assess their accuracy in predicting dose rates for spent nuclear fuel. It highlighted discrepancies in gamma flux modeling and identified best practices for radiological assessments.

Sustainable transition studies:

The Transition Towards a Sustainable Nuclear Fuel Cycle[5] report analysed global scenarios for transitioning from light-water reactors to fast reactors. It evaluated resource consumption, waste reduction, and infrastructure needs over time. This work provided a strategic framework for achieving long-term sustainability in nuclear fuel cycles, particularly by emphasising recycling and advanced reactor technologies.

Uncertainty analysis:

In the Effects of the Uncertainty of Input Parameters on Nuclear Fuel Cycle Scenario Studies[6], EGAFCS investigated the impact of parameter variability on scenario outcomes. By assessing 17 critical parameters across 22 outputs, this study provided methodologies to quantify and mitigate uncertainties in fuel cycle modeling, enhancing confidence in policy decisions and system designs.

(2) Current Activities

Building on its foundational work, the EGAFCS is pursuing two major initiatives to further enhance nuclear fuel cycle analysis and collaboration.

The Online Catalogue for Fuel Cycle Scenario Codes is a direct extension of previous benchmarking efforts. It consolidates tools used for nuclear fuel cycle modelling and simulation into a structured framework, categorised by general information, model details, outputs, features, and programming. By promoting transparency and accessibility, this initiative facilitates collaboration and enhances the usability of tools such as ANICCA, COSI, DYMOND, and VISION.

The Comparative Study of Alternative Options for Co-operative Transuranic Elements Management evaluates various strategies for managing transuranic elements (TRUs) such as plutonium, neptunium, americium, and curium, which are byproducts of nuclear fuel irradiation. These elements pose challenges in waste management due to their heat generation, radiotoxicity, and safeguards concerns. The study models and assesses different TRU management approaches using nuclear fuel cycle scenario simulations. Objectives include evaluating the TRU burning potential of different reactor fleets, assessing the feasibility of achieving equilibrium TRU inventory states, and comparing nuclear fuel cycle simulation codes and physics models. Additionally, the study explores the technical feasibility of reusing spent nuclear fuel from one entity phasing out nuclear power in another adopting an advanced nuclear fuel cycle, aiming to reduce inventory impact and provide fissile material for fuel cycle transitions.

(3) Future Activities

The EGAFCS is set to evaluate the long-term global impacts of different nuclear fuel cycle scenarios up to 2100, focusing on a potential tripling of nuclear capacity by 2050. The study will address:

- Front-end factors: Uranium resource needs, and enrichment, conversion, and fabrication capacities.
- Back-end factors: Spent fuel inventories, waste management, and disposal requirements.
- Economic aspects: Costs related to fuel cycle transitions.

The study will occur in two phases: first, assessing two reference cases - no capacity growth and tripled nuclear capacity by 2050 - and second, conducting parametric analyses to explore variations in reactor technologies and scaling rates. This work will provide guidance on sustainable nuclear energy growth and waste management strategies.

2. Expert Group on Innovative Fuel Elements (EGIFE)

EGIFE focuses on addressing technical challenges in the development of innovative nuclear fuels, including oxide, metal, nitride, and carbide fuels. These fuels are designed for use in advanced nuclear fuel cycles and Gen IV reactor systems. The group's work also includes the study of driver fuels, such as uranium and uranium-plutonium fuels, and fuels dedicated to minor actinide transmutation, aimed at reducing radioactive waste and improving fuel efficiency. The EGIFE conducts joint and comparative studies to support the implementation of these innovative fuels in advanced nuclear systems.

(1) Past Activities

The Expert Group on Innovative Fuel Elements (EGIFE) has conducted critical studies on advanced nuclear fuels, focusing on their fabrication, performance, and applicability in fast reactors. Two landmark reports highlight these efforts.

The State-of-the-Art Report on Innovative Fuels for Advanced Nuclear Systems[7)] provided a comprehensive review of fuels containing minor actinides (MA) for advanced nuclear systems, particularly fast reactors. This report explored various fuel types, including metal, oxide, nitride, and dispersion fuels, assessing their fabrication methods, irradiation performance, and safety criteria. It concluded that while metal fuels are well-documented and exhibit promising properties, fuels such as nitride and dispersion types require further development. The study also emphasized the challenges in handling MA-bearing fuels, including fabrication in remote environments and helium gas management, and outlined the technology readiness levels (TRLs) for each fuel type.

The Benchmark Study on Innovative Fuels for Fast Reactors with Fuel Performance Codes[8)] evaluated the predictive capabilities of fuel performance codes for metal and oxide fuels. Using irradiation data from international experiments, the study compared code predictions against experimental results to identify gaps in modelling and areas for improvement. It found that while the presence of minor actinides (up to 5%) had minimal impact on overall fuel behaviour under current conditions, more advanced irradiations are needed to fully understand MA effects at higher burn-ups and transmutation rates.

These studies have provided the foundational knowledge required to advance the design and implementation of innovative fuels in fast reactors, while identifying areas for future research and development.

(2) Current and Future Activities

Building on the previous benchmark and state-of-the-art assessment, EGIFE is currently engaged in two significant activities that address key technical challenges associated with advanced nuclear fuels.

Phase 2 of the Benchmark Study on Innovative Fuels for Fast Reactors focuses on code-to-code comparisons under transient conditions, specifically evaluating Unprotected Transient Over Power (UTOP) and Unprotected Loss of Flow (ULOF) scenarios for oxide and metal fuels. Five simulation codes are included in the benchmark: CEPTAR, GERMINAL, and TRANSURANUS for oxide fuels, and ALFUS and MACSIS for metal fuels. These comparative studies aim to validate and improve the predictive accuracy of fuel performance codes under these challenging conditions. The study also includes recommendations for fuel properties for mixed oxide (MOX) and UPuZr fuels, based on expertise provided by EGIFE, as well as cladding property assessments for materials such as 9Cr-ODS, HT9, and 15/15Ti conducted by the NEA Expert Group on Structural Materials (EGSM).

In parallel, EGIFE has drafted an official report on fuel properties for Gen IV systems, focusing on the thermal and mechanical characteristics of oxide and metal fuels. This work represents a significant milestone as it consolidates data from experimental research over the past two decades, addressing critical parameters such as lattice parameters, thermal conductivity, heat capacity, and phase transitions. The recommendations aim to enhance the integration of experimental data into predictive models, ensuring consistency in the properties used for reactor design and fuel performance assessments. Experts meticulously analysed datasets from international research programs, selecting validated correlations and identifying gaps for future research.

Together, these activities reinforce EGIFE's commitment to advancing the understanding and implementation of innovative fuels, ensuring their performance and safety under operational and transient conditions. By addressing both modeling challenges and experimental data consolidation, EGIFE continues to support the development of sustainable and efficient fuel cycles for advanced nuclear systems.

3. Expert Group on Fuel Recycling and Waste Technology (EGFRW)

EGFRW focuses on advancing separation processes critical to the recycling of spent nuclear fuel. Its scope includes reprocessing, waste treatment, and the recycling and reuse of spent fuel components, excluding long-term storage technologies. The group's objectives are to perform technical assessments of separation processes for current and future nuclear fuel cycles, recommend collaborative international efforts to enhance these processes, and maintain the International Database on Extractant Ligands (IDEaL). Additionally, the EGFRW conducts analyses of Molten Salt Reactor (MSR) fuel cycle chemistry to identify existing data, gaps, and research needs, supporting the development of efficient and sustainable nuclear fuel recycling technologies.

(1) Past Activities

EGFRW has focused on advancing separation and recycling technologies for spent nuclear fuel, producing foundational studies and technical assessments to support future fuel cycle innovations.

The State-of-the-Art Report on the Progress of Nuclear Fuel Cycle Chemistry[9)] provided a comprehensive review of separation processes for recycling technologies, examining head-end, hydrometallurgical, and pyrochemical techniques. It assessed key advancements in spent fuel reprocessing, including technologies like PUREX and UREX+, and identified gaps in achieving efficient, sustainable, and proliferation-resistant fuel cycles. The report also emphasised the integration of emerging technologies such as hybrid aqueous-pyrochemical methods for handling challenging waste streams.

The Spent Nuclear Fuel Reprocessing Flowsheet report[10)] collected and analysed reprocessing methodologies developed by NEA member countries, covering aqueous, pyrochemical, and fluoride volatility processes. This detailed work provided flowsheets, material balances, and assessments of reprocessing technologies, focusing on reducing radiotoxicity and optimising resource recovery. Key processes like pyroprocessing and advanced PUREX variants were examined for their potential in managing long-lived radionuclides and reducing high-level waste volumes.

The Review of Operating and Forthcoming Experimental Facilities[11)] catalogued international facilities supporting advanced recycling research. It highlighted capabilities for experimental R&D, including pilot-scale operations and testing of innovative recycling techniques. This work established a collaborative framework for utilising shared infrastructure to accelerate advancements in fuel recycling technologies.

These activities have laid a strong foundation for enhancing nuclear fuel recycling by improving separation efficiency, reducing waste, and fostering international collaboration. They continue to inform ongoing efforts to advance recycling technologies for future nuclear fuel cycles.

(2) Current Activities

EGFRW continues its efforts to advance recycling technologies for spent nuclear fuel with a focus on innovative approaches to resource recovery and waste minimisation. One key activity explores recycling and reusing valuable materials from spent nuclear fuel beyond traditional nuclear applications. This soon-to-be published report examines the recovery of rare earth elements, platinum group metals, and other materials for industrial, medical, and critical supply chain applications. The report highlights the increasing relevance of sustainability in industrial practices, addressing the economic and societal benefits of recycling, such as reducing geological disposal needs and leveraging valuable components like actinides for emerging uses, including medical isotopes and radiological research. Challenges such as high reprocessing costs and technical limitations are identified, but advances in recycling methods and process optimization are emphasized as paths forward.

Complementing this, the EGFRW has also launched an international benchmarking exercise on solvent extraction codes and process modelling to refine solvent extraction processes critical to the nuclear fuel cycle. This exercise evaluates the predictive accuracy of various solvent extraction simulation codes through international collaboration. Participating organizations apply their models to standard case studies, comparing results for consistency and accuracy in areas such as the behaviour of actinides and lanthanides during separation. The benchmarking aims to identify gaps in current modelling capabilities, harmonise methodologies, and improve the reliability of solvent extraction processes for applications in nuclear fuel reprocessing.

(3) Future Activities

EGFRW plans to address the critical challenges associated with the treatment and reprocessing of fuel in MSRs. This initiative aims to develop the technical foundation needed to ensure sustained reactor operation, efficient isotope removal, and environmentally responsible waste management. The focus on MSRs within this group reflects a growing interest, among the Expert Group member states, in the MSR's potential for sustainable nuclear fuel cycles.

MSR fuel presents unique opportunities and challenges compared to conventional solid fuels. Its treatment during and after irradiation is essential for reactor operation and licensing. However, significant development in this area remains limited. To address this gap, the EGFRW intends to define the terminology, goals, and processes required for molten salt fuel cycles. Particular attention will be given to waste treatment and storage, with an emphasis on environmental and economic impacts.

The primary objective of this activity is to identify the isotopes that must and might have to be removed from molten salt fuel to sustain fission reactions without compromising reactor performance. The group will undertake the following activities:

1. Establish a consistent terminology for MSR fuel cycles to standardise communication and research frameworks.
2. Review and evaluate separation techniques for removing isotopes with adverse impacts on reactor performance.
3. Assess available technologies for waste treatment and management, with a focus on identifying isotopes that require immediate or periodic removal.

To sustain the long-term operation of MSRs, the activity will address four main areas:

1. Terminology: Develop robust definitions for molten salt fuel cycle processes and validate them against existing frameworks to ensure consistency and applicability.

2. Isotope removal: Conduct a comprehensive review of data to identify chemical elements and isotopes that negatively impact the neutronic and chemical properties of molten salt. Recommendations will be made on removal timing and priorities, depending on reactor design and operational requirements.

3. Separation techniques: Evaluate existing techniques to identify their capabilities and limitations for isotope removal, outlining areas for further research and development.

4. Waste treatment: Define waste streams generated during isotope removal and propose methods for processing and managing these materials sustainably.

This future activity represents a vital step toward advancing MSR technology and optimising molten salt fuel cycles. The findings will provide actionable insights for researchers and developers, addressing technical, environmental, and operational challenges while contributing to the broader goals of sustainability and innovation in nuclear energy.

4. Expert Group on Reactor Coolants/Components Technology (EGCoCoT)

EGCoCoT focuses on the scientific and technical aspects of reactor coolants, liquid sodium and heavy liquid metals, and their interactions with structural components. The group's objectives encompass assessing environmental effects on materials' behavior, including corrosion and mechanical properties under irradiation, and evaluating coolant and cover gas issues pertinent to radiological impact assessments and operational considerations. Additionally, EGCoCoT addresses thermal-hydraulic behavior of coolants, aiming to enhance the understanding of flow distribution, temperature stratification, and coolant-structure interactions. Through these efforts, EGCoCoT contributes to the development of construction codes, licensing frameworks, and operational guidelines, thereby supporting the safe and efficient advancement of nuclear reactor technologies.

(1) Past Activities

EGCoCoT has made significant contributions to advancing the understanding of heavy liquid metals (HLMs), particularly lead and lead-bismuth eutectic (LBE), for nuclear reactor applications. One key initiative culminated in the publication of the 2015 Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies[1)], which consolidated critical experimental and theoretical knowledge on material compatibility, corrosion behavior, and thermal-hydraulic properties. This comprehensive resource supported the safe design and operation of HLM-cooled systems such as lead-cooled fast reactors and accelerator-driven systems, while also identifying gaps in data and areas for further research.

Another major effort was the Structural Materials Data Management Survey[12)], which reviewed practices for managing and standardizing data on the behaviour of structural materials in contact with HLMs. This survey highlighted challenges in data collection and qualification, particularly for corrosion and mechanical properties under liquid metal environments. It emphasised the need for a centralised database to support reactor safety assessments and design codes, laying a foundation for enhanced international collaboration and the development of robust standards for HLM applications. These activities have provided essential tools and insights for advancing the safe use of HLMs in nuclear systems.

(2) Current Activities

EGCoCoT is currently producing a comprehensive state-of-the-art report on the effects of liquid metal coolants on materials. This project systematically examines the interactions between liquid metal coolants—specifically sodium (Na), lead (Pb), and lead-bismuth eutectic (LBE)—and the structural materials used in Sodium-cooled Fast Reactors (SFRs) and Lead-cooled Fast Reactors (LFRs). The primary objective is to provide a detailed, technically rigorous assessment of the latest research on how these coolants affect material properties under various operational conditions.

This activity addresses the multifaceted challenges posed by liquid metal coolants in fast reactors. While these coolants offer superior heat transfer properties and neutron economy, they introduce complex thermal-hydraulic phenomena and aggressive chemical environments that can lead to material corrosion. The report aims to document current knowledge, expertise, and research and development gaps in specific mechanisms such as thermal and mechanical loads, radiation-induced damages, and mass transfer phenomena, offering a granular analysis of their impact on material integrity.

IV. Workshops

The WPFC plays a crucial role in fostering collaboration and advancing knowledge in nuclear science by organizing workshops on critical topics related to fuel cycles, waste management, and reactor technologies. These workshops bring together international experts, researchers, and industry representatives to exchange ideas, share the latest research findings, and identify challenges and opportunities for further innovation. Two recent workshops exemplify the WPFC's commitment to driving progress in these fields.

The Workshop on Fuel Cycle Chemistry for MSR Technologies, held in Vienna from October 2-6, 2023, was co-organised by the NEA and the IAEA. It gathered 44 participants from 13 countries, including MSR developers, regulators, and industry experts. The workshop featured technical sessions, breakout discussions, and panel presentations that addressed experimental underpinning, irradiations, and the treatment of irradiated fuel. Key proposals for future activities included establishing a taxonomy of MSR fuel cycles, developing state-of-the-art guidelines for measurements and analyses, and identifying irradiation needs for fuel qualification.

The 16th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation (16IEMPT) took place at the NEA Headquarters from October 24-27, 2023. This meeting involved over 90 participants from 16 countries and 3 international organisations. The event included seven oral sessions, a poster session, and two special panel discussions commemorating 30 years of IEMPT while exploring its future directions. Key takeaways included an emphasis on the benefits of closed fuel cycles, improved stakeholder communication, and fostering connections with the disposal community.

V. Conclusion

Through benchmarking studies, state-of-the-art reports, and workshops, the WPFC has addressed critical challenges in areas such as nuclear fuel recycling, advanced fuel elements, reactor coolant technologies, and sustainable fuel cycle scenarios. The groups' efforts have supported global initiatives, such as the commitment to triple nuclear capacity by 2050, by providing actionable insights on sustainability and efficiency of nuclear systems.

The groups' current activities underscore WPFC's role as a leader in collaborative research and knowledge dissemination, in the field of advanced fuel cycles. The Workshop on Fuel Cycle Chemistry for Molten Salt Reactors and the 16th Information Exchange Meeting on Partitioning and Transmutation brought international experts together and allowed for technical exchanges and cooperative projects. Ongoing activities include refining solvent extraction processes, evaluating the impacts of liquid metal coolants on materials, and advancing recycling technologies to reduce waste and recover valuable resources. These efforts are complemented by the production of technical guidelines, databases, and readiness assessments for emerging technologies.

Looking forward, WPFC's planned activities, including the evaluation of molten salt reactor fuel cycles, long-term assessments of nuclear capacity scenarios, and a study of the possibility to accelerate the nuclear fuel qualification process highlight the group's commitment to addressing future energy challenges. By focusing on collaboration, technical excellence, and practical solutions, WPFC continues to have significant contributions to the nuclear fuel community.

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