ISSN 1831-9424

European Commission

# JRC PORTFOLIO 04

# SAFETY OF NUCLEAR TECHNOLOGY IN SUPPORT OF THE TRANSITION TOWARDS CLIMATE NEUTRALITY

## Activity Report 2023

Joint Research Centre

EUR 40049

EU Science Hub

https://joint-research-centre.ec.europa.eu

JRC138993

EUR 40049

| | | | | |
|---|---|---|---|---|
| Print | ISBN 978-92-68-20806-9 | ISSN 1018-5593 | doi:10.2760/1662995 | KJ-01-24-050-EN-C |
| PDF | ISBN 978-92-68-20805-2 | ISSN 1831-9424 | doi:10.2760/3227038 | KJ-01-24-050-EN-N |

Luxembourg: Publications Office of the European Union, 2024



How to cite this report: European Commission, Joint Research Centre, Aldave De Las Heras, L., Bremier, S., Benes, O., Colineau, E., Eloirdi, R., D`Agata, E., Kopecky, S., Haehner, P., Hult, M., Manaud, J., Martin, O., Mooren, E., Papaioannou, D., Serrano Purroy, D., Staicu, D., Seibert, A., Tanarro Colodron, J., van Uffelen, P. and Wiss, T., *JRC Portfolio 04 - Safety of Nuclear Technology in Support of the Transition towards Climate Neutrality,* Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/3227038, JRC138993.

# JRC PORTFOLIO 04

# SAFETY OF NUCLEAR TECHNOLOGY IN SUPPORT OF THE TRANSITION TOWARDS CLIMATE NEUTRALITY

## Activity Report 2023

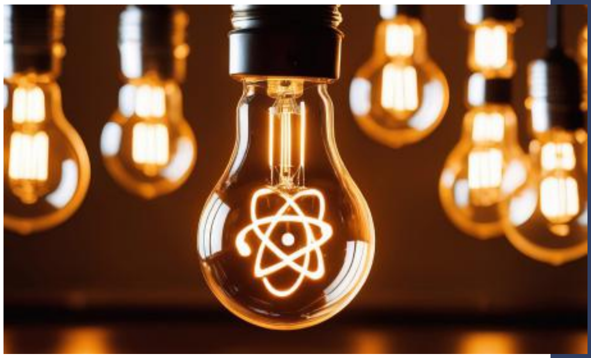
***Main Authors: Laura Aldave de las Heras and Stephane Bremier***

*Contributors: Benes, O., Colineau, E., Eloirdi, E., D'Agata, E., Kopecky, S., Haehner, P., Hult, M., Manaud, J., Martin, O., Mooren, E., Papaioannou, D., Serrano Purroy, D., Staicu, D., Seibert, A., Tanarro Colodron, J., Van Uffelen, P., Wiss, T.*

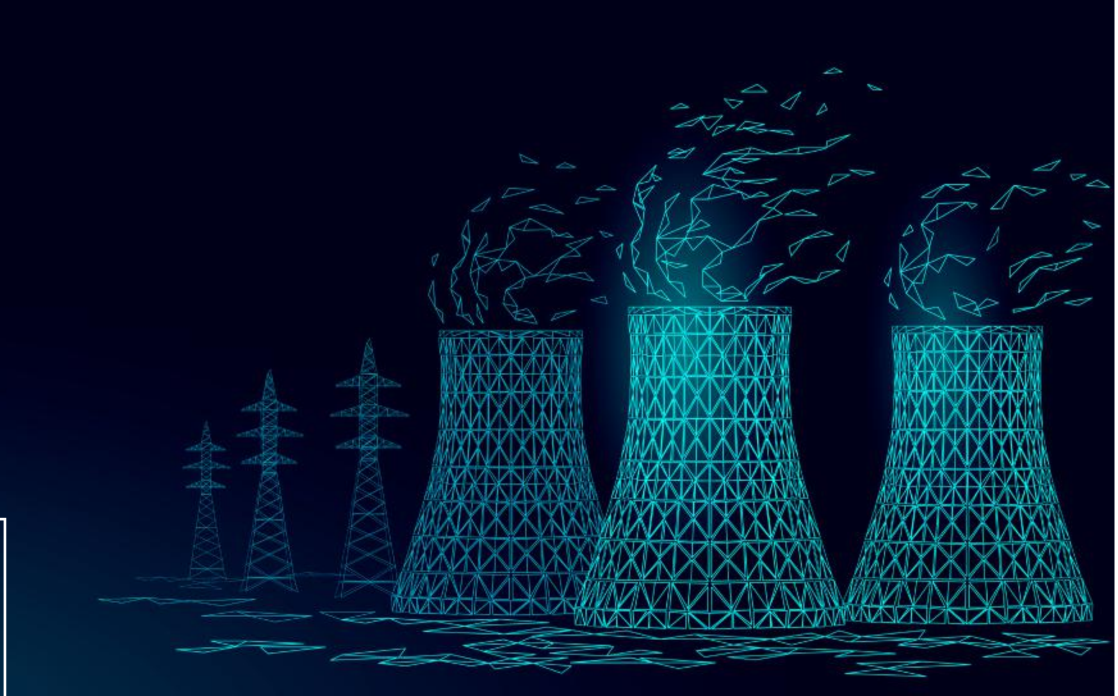
2024

# Content





DESIGNER Laura Aldave de las Heras
PHOTOS Adobe stock





# Editorial

The European Union (EU) aims to be climate-neutral by 2050, becoming an economy with net-zero greenhouse gas emissions. This objective is at the heart of the European Green Deal and in line with the EU's commitment to global climate action under the Paris Agreement. Through the Taxonomy Regulation Complementary Delegated Act, the Commission has concluded that nuclear energy, subject to strict safety and environmental conditions, can play a role in the transition towards climate neutrality in line with the Green Deal. This is also a practice of some EU Member States. It encourages the development and improvement of safety standards for nuclear technologies, including advanced waste-minimising technologies and new nuclear energy generation projects.

This portfolio ensures continuity between **short- and long-term research and competences** in the context of the energy transition and decarbonisation of the EU economy by 2050, through a number of **research activities that contribute to safety optimisation of existing and new nuclear technologies**.

# EXECUTIVE SUMMARY

"PF4 implements the Euratom Research and Training Programme"

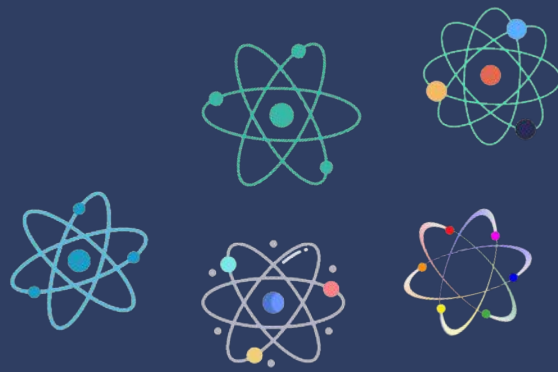
The report emphasises the contribution of **JRC Portfolio 4** to the safety of nuclear technology in support of the EU's energy and climate objectives. Key initiatives in 2023 focused on the safety of the nuclear life cycle, waste management, expanding nuclear applications across various non-energy production sectors, and open access to the JRC's unique nuclear infrastructure.

**Nuclear reactor safety** is essential for ensuring that reactors operate without posing threats to citizens or the environment. This involves robust engineering designs, stringent operational protocols, and regular safety assessments. Significant JRC efforts are directed towards improving the safety of nuclear reactors and components. The research includes design-basis analysis and beyond-design-basis evaluation of reactor systems, focusing on the ageing and l**ong-term operation** of nuclear plants and radiation damage studies.

**Fuel safety** research at the JRC develops tools and data for analysing fuel behaviour under normal and incident conditions, including high-temperature scenarios. This research spans various reactor fuel types, such as advanced technological fuels for light-water reactors and mixed oxide fuels for fast reactors.

The TRANSURANUS **fuel performance code** is a key instrument for the thermal, mechanical, and neutron-physical analysis of fuel rods in nuclear reactors, aiding safety assessments worldwide. The code is applied to design and **license nuclear fuel** by various European research centres, universities, nuclear safety authorities, and industrial partners.

The JRC supports EU Member States by providing policy support, conducting research, and facilitating international cooperation to ensure **safety in the long-term storage and disposal**



of **conventional and advanced** **fuels**. The JRC's work is part of the uropean **Joint Programme on** **Radioactive Waste Management** EURAD 1 and 2), aligning with ey strategic platforms such as GDTP and SNETP. In 2023, the RC contributed to the **fuel cycle** hrough partnerships with ENRESA nd CIEMAT (Spain) on Raman pectrometry, in collaboration with Hasselt University (Belgium) on the mmobilisation of radionuclides sing sustainable eco-friendly naterials, and identified new esearch avenues with IRSN and CEA (France). It also engages n OECD/NEA projects for **post-** **accident waste management**.

ctivities performed at the JRC ave **expanded the use of nuclear** **echnology beyond energy** **production**. Prominent key areas nclude **medical applications** vhere the JRC supports the EU's Beating Cancer Plan with advanced uclear techniques and **space** **exploration** with the development f radioisotope power systems or space missions, contributing o European space policy.

he **Karlsruhe Nuclide Chart**, which elebrates its 65th anniversary n 2023, contains structured and ccurate information for scientists and students. Beyond the more traditional physical sciences such as health physics, radiation protection and nuclear and radiochemistry, the chart is now widely used in life and earth sciences. It has proven great didactic value for education and training in nuclear sciences.

The JRC **Central Bureau for Nuclear Measurements** under the Euratom Treaty promotes a standard **system for nuclear measurements**. It provides essential nuclear data for energy, the environment, medicine, and security applications through evaluated libraries and **high-precision measurements** at its GELINA and MONNET accelerators. The JRC supports international projects and provides **crucial** for calibration, safety, and waste management **data**.

Access to the **JRC's nuclear research infrastructure** is essential for offering high-quality research and innovation opportunities to EU Member States, associated countries organisations, and researchers through a dedicated **open-access scheme**. Financial arrangements with DG Research and Innovation support external users' travel and subsistence, promoting training and mobility among academia, research centres, and industry. The scheme, utilising facilities in Karlsruhe, Geel, and Petten, has seen 83 proposals accepted since 2020, with about 70% involving students and young researchers, resulting in over 50 peer-reviewed scientific publications. This initiative fosters European cooperation, strengthens the European Research Area, and addresses the critical need for **developing the next generation of nuclear scientists and engineers**.

The JRC supports **EU nuclear technology policies** through its Euratom **Foresight cycle**, which includes scanning, distilling, sense making, deep diving, and policy briefing. The annual Horizon Scanning process identifies critical topics, such as the role of nuclear start-ups, the potential for decarbonising hard-to-abate sectors and integrating digital technologies. This foresight work highlights emerging trends and identifies 11 critical topics for the future of nuclear technology in the EU as a roadmap for addressing opportunities and threats in nuclear technology for the 2033 and 2053 horizons.

Finally, this report discusses recent findings on **public attitudes** in some European Member states and third countries with respect to clean energies including nuclear energy.

# NUCLEAR ENERGY 2023 in review

01

Nuclear power is making a resurgence in the EU energy landscape after an eventful 2023 year, with France spearheading the defence of nuclear energy. After three years of intense negotiations, nuclear energy officially joined the list of “transitional” energies in the **EU’s green taxonomy** on 1 January 2023.

The effects of the energy crisis driven by the war in Ukraine, EU countries, all of whom have collectively decided to steer away from Russian gas, have become more willing to open up to **nuclear energy**. In France and eastern EU countries, nuclear power is increasingly considered a viable solution for achieving **carbon neutrality by 2050**.

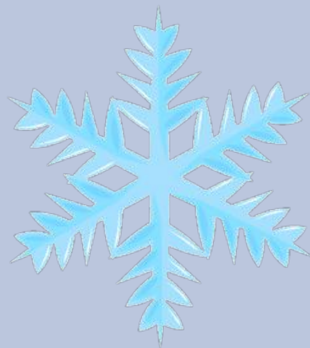
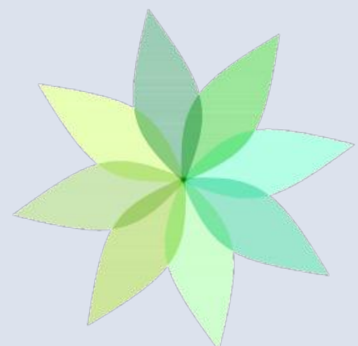
On 1st February, France, Romania, Bulgaria, Poland, Slovenia, Croatia, Slovakia, Hungary, and Czechia called upon the European Commission to include **low-carbon hydrogen** from nuclear electricity in the EU’s renewable hydrogen targets. The demand is based on the **principle of technological neutrality** and member states’ **sovereignty** and **competence** to decide on their **energy mixes**, as defined in the EU treaties. The Parliament’s Committee on Industry, Research, and Energy (ITRE) adopted a definition of **low-carbon hydrogen** on 4 February. This definition aligns low-carbon hydrogen with renewable hydrogen for decarbonising the European economy. On 11 February, The European Commission introduced rules for labelling low-carbon hydrogen produced from nuclear electricity as “renewable”, opening an unexpected political dimension. France urged the European Commission to recognise the contribution of nuclear-derived hydrogen to the targets set out in the European Renewable Energy Directive (RED III). On 29 March the EU sought a compromise over the **nuclear’s role in renewable energy goals**, and on 16 June the European Commission recognised the role of nuclear energy in achieving the objectives of decarbonising the EU economy.

On 28 February 11 EU countries launched an **alliance for nuclear power** in Europe to enhance the cooperation across the nuclear supply chain and promote common industrial projects, including new technologies, such as small modular reactors (SMRs). On 16 May, 16 European countries (France, Belgium, Bulgaria, Croatia, the Czechia, Finland, Hungary, the Netherlands, Poland, Romania, Slovenia, Slovakia, Estonia, Sweden, Italy as observer, and the UK as guest) participating in the nuclear alliance agreed to prepare a roadmap to develop an integrated European nuclear industry, reaching **150 GW of nuclear power** capacity in the EU’s electricity mix by 2050. In July, the nuclear alliance met for the fourth time in Valladolid (Spanish Presidency) and adopted a **roadmap for a new strategy** on the use of nuclear energy for the EU, calling for equal EU treatment with renewables.

On 16 March the European Commission unveiled a proposal for the **Net-Zero Industry Act** to promote the manufacturing of low-carbon technologies in the EU in response to the US Inflation Reduction Act. The European Parliament’s ITRE Committee reintroduced nuclear in the EU’s net-zero industry list on 18 July and voted on 25 October to put nuclear power back in the EU’s net-zero industry list. Finally, the European Parliament voted (21 November) to include 17 technologies, including nuclear energy, in the EU’s Net-Zero Industry Act, paving the way for talks with EU member states to finalise the law.

On 4th April, the European Commission announced the ambitious Declaration on ‘EU Small Modular Reactors (SMRs) 2030: Research & Innovation, Education, & Training. On 7 September the European Parliament ITRE Committee called for the creation of a new joint undertaking on **small modular reactors (SMRs)**, and the EU’s Energy Commissioner supported the development of an **industrial alliance** on small modular reactors at the 16th European Nuclear Energy Forum in Bratislava (7 November). On 12 December the European Parliament backed the EU push for small nuclear reactors and adopted an “own initiative report” on small modular reactors (SMRs), signalling the importance of these technologies for Europe’s future energy system. The report highlights the benefits of nuclear energy, specifically SMRs, in decarbonising Europe’s energy mix, ensuring supply security, and supporting hard-to-abate sectors such as industry. The next day, 22 countries pledged to triple their nuclear capacity to cut fossil fuels (COP28).

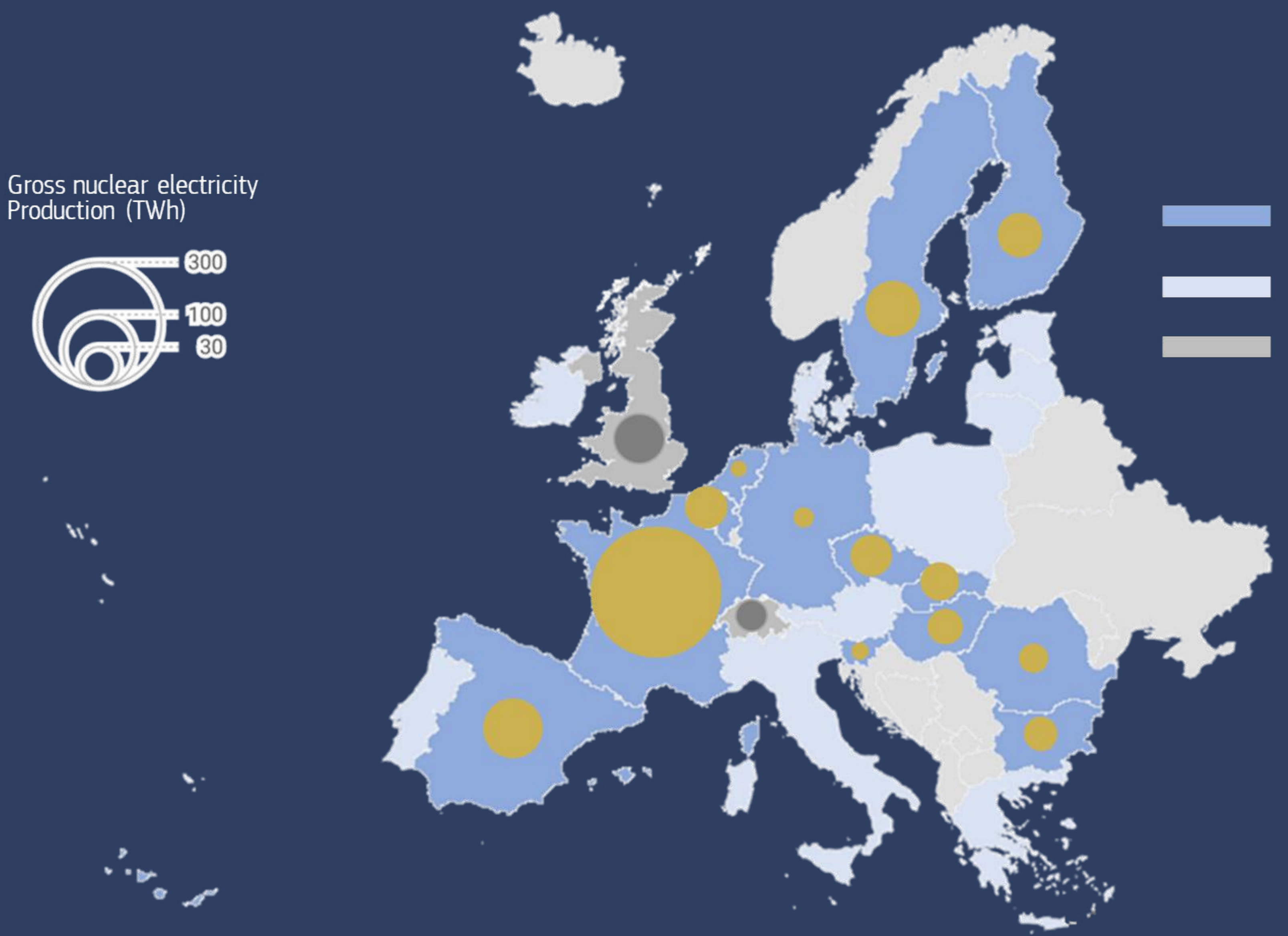
# 2023 in Review

| | | | |
|---|---|---|---|
| **JAN** |  | 1st: Nuclear energy officially joined the list of transitional energies in the EU's green taxonomy on 1 January 2023. | 12th: Swedish government frees up legislation on nuclear expansion.<br>31st: Belgium to shut down Tihange 2 nuclear reactor. |
| **FEB** | | 1st: Nine EU want low-carbon hydrogen included in bloc's renewables goals.10th: EU Parliament backs pro-nuclear definition of 'low-carbon' hydrogen. | 11th: France wins recognition for nuclear in EU's green hydrogen rules.<br>27th: Paris drafts European 'nuclear alliance'. |
| **MAR** | | 1st: Eleven EU countries launch alliance for nuclear power in Europe. 16th: The European Commission unveiled its proposal for a Net-Zero Industry Act. | 29th: EU seeks compromise over nuclear's role in renewable energy goals. |
| **APR** | 4th: The European Commission announces the ambitious Declaration on 'EU Small Modular Reactors (SMRs) 2030.<br>15th: Germany closed its last nuclear power plants and ends 60 years of nuclear energy. | 16th: Olkiluoto 3 (OL3) 1.6 GW nuclear reactor, Europe's largest, begins regular output.<br>17th: The Nuclear Fuel Alliance was established by the US, France, Japan, Canada, and the UK at the G7 summit in Japan to counter Russia's influence on energy supply chains. |  |
| **MAY** | 11th: Italy / Parliament votes in favour of return to nuclear power. | 16th: Nuclear alliance aims for 150 GW of nuclear capacity in EU by 2050. | |
| **JUN** |  | 21st: Sweden adopts '100% fossil-free' energy target, easing way for nuclear. | 30th: Belgian government signs nuclear extension deal with France's Engie. |
| **JUL** | | 11th: The nuclear alliance meets for the fourth time in Valladolid and adopts a roadmap for a new strategy on the use of nuclear energy for the EU. | 20th: EU Lawmakers reintroduce nuclear in EU's net-zero industry list. |
| **AUG** | 16th: Fukushima ALPS-treated water release plan based on safety, scientific evidence. |  | 28th: Slovakia stops relying on Russia for nuclear fuel. |
| **SEP** | 7th: European Parliament ITRE committee calls for the creation of a new joint undertaking on small modular reactors (SMRs). | | 7th: Critical raw materials: MEPs back plans to secure EU's own supply and sovereignty. |
| **OCT** |  | 23th: The European Parliament's ITRE committee votes to put nuclear back in EU's net-zero industry list. | 26th: Bulgaria starts nuclear project with US technology. |
| **NOV** | | 7th: The EU's Energy Commissioner backed the development of an industrial alliance on small modular reactors at the 16th European Nuclear Energy Forum in Bratislava. | 21st: EU Parliament backs extensive net-zero industry 'wishlist', including nuclear. |
| **DEC** | | 12th: Parliament backs EU push for small nuclear reactors.<br>13th: 22 Countries Pledge to Triple Nuclear Capacity in Push to Cut Fossil Fuels (COP28). | 19th: Sweden and France strengthen cooperation on nuclear.<br>20th: French-led nuclear alliance calls for new 'low-carbon' directive. |

# Facts & Figures 2023

In 2023, EU Member States with nuclear electricity production generated 618.5 terawatt hours (TWh) of nuclear electricity, which is much lower than the 2004 peak of 900 TWh. Half of the EU's nuclear electricity was produced in France (54.3% of the total EU nuclear energy production; 335.7 TWh). Other large producers of nuclear power in the EU were Spain (9.2%; 56.8 TWh), Sweden (7.8%; 48.4 TWh), Finland (5.5%; 33.9 TWh), Belgium (5.4%; 33.4 TWh), and Czechia (4.9%; 30.4 TWh). Together, these six countries generated more

## Nuclear Energy in the EU, 2023
## Gross nuclear electricity production (TWh)




Note: The nuclear power plant located in Slovenia is 50% co-owned by Croatia. Germany closes its last NPPs in April 2023. D than 87% of the total amount of electricity from nuclear power plants located in the EU. According to LowCarbonPower for 2023, nuclear energy is the largest single source of electricity generation in the EU, accounting for 23% of all electricity produced. The countries with the largest share of nuclear energy in their energy mix at the time were France (65.3%), Slovakia (61.9%), Finland (41.5%), Bulgaria (40.4%), and Czechia (39.9%). In 2021, nuclear energy available in the EU constituted 13% of Europe's energy mix.

EU MSs with nuclear electricity production

EU MSs with no nuclear electricity production

UK, CHE

Data from Ember.

**618.5 TWh**

nuclear electricity generation

**54%**

French fleet

**23%**

EU's electricity mix

## France

The EU Member States rely on nuclear electricity to varying degrees. In 2023, France produced 65% of its electricity in nuclear power plants, which is the largest share of any Member State.

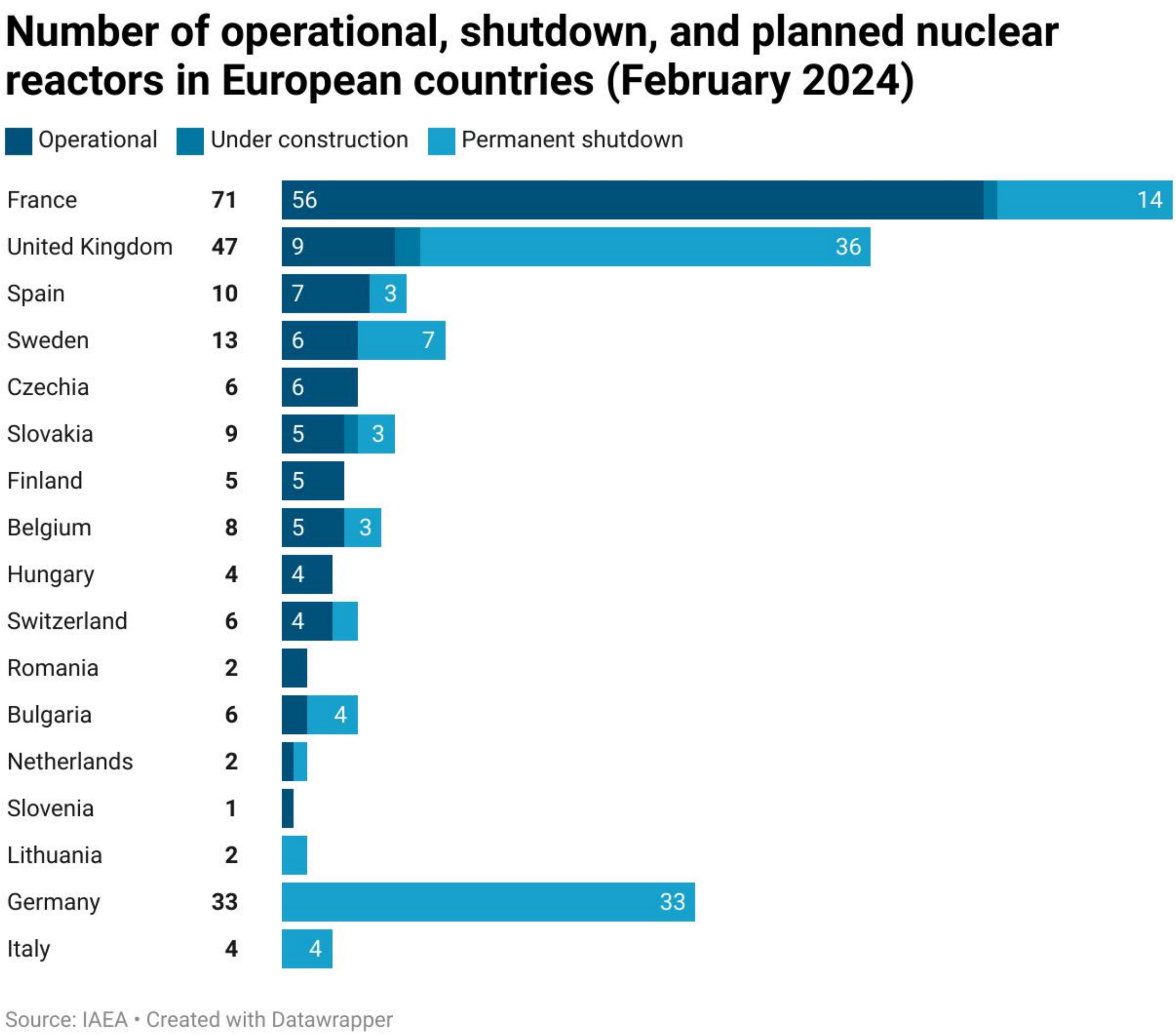
## EU largest single source of electricity

As a primary low-carbon source, nuclear energy has helped avoiding 21.4 Giga tons of the $CO_2$ emissions in the EU in the last 50 years.

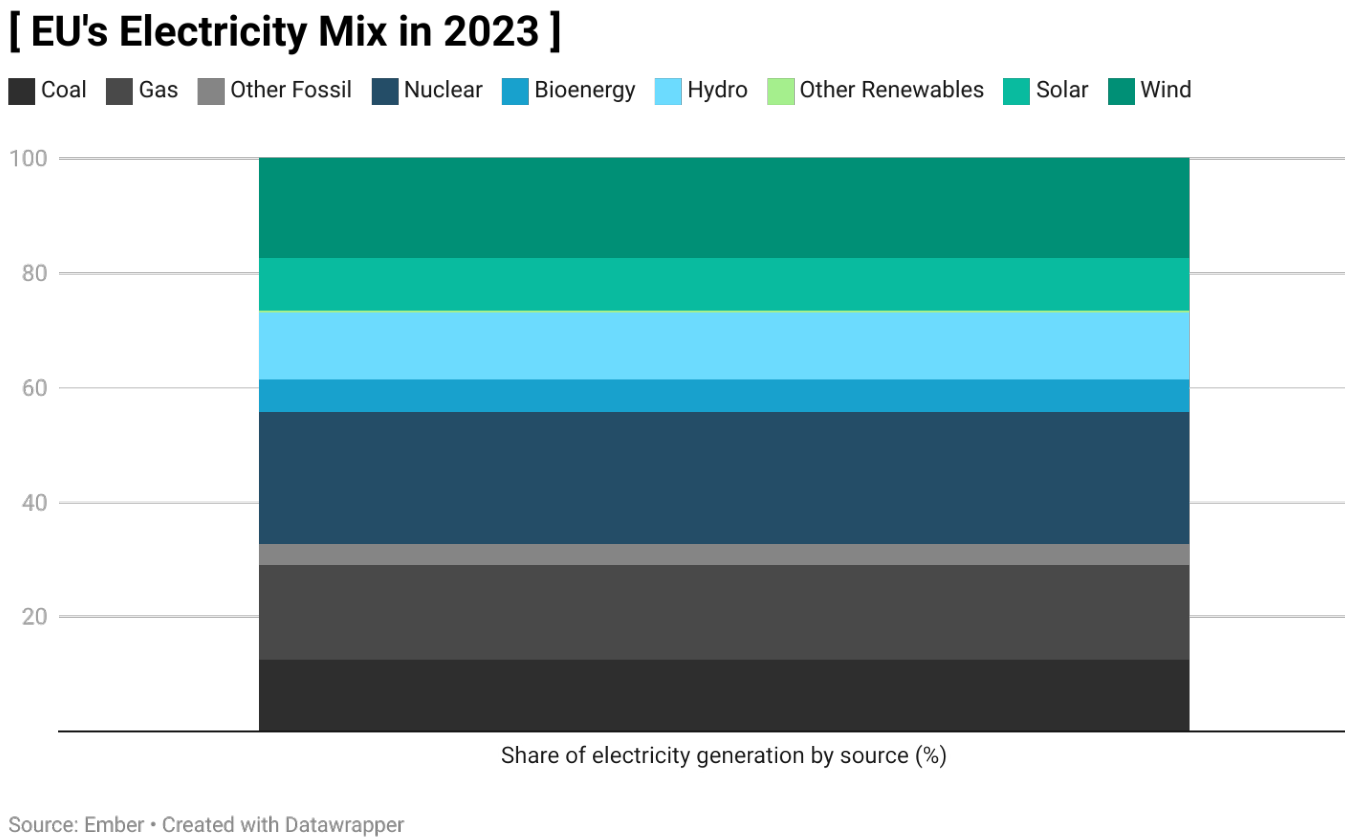
The EU's 100 nuclear reactors operate in 12 of 27 Member States. This is a downward trend, as there were 106 reactors in 2021 and 109 reactors at the beginning of 2020. Over half of the EU's operating nuclear reactors are located in France (56). Other countries with nuclear reactors include Spain (seven), Sweden (six), Czechia (six), Belgium (five), Finland (five), Slovakia (five), Hungary (four), Bulgaria (two) and Romania (two). The Netherlands and Slovenia (its plant is 50 % co-owned by Croatia) have only one nuclear power plant. Germany closed all its power plants in April 2023.

Europe's approach to nuclear energy varies significantly. As laid out in their **national energy and climate plans,** some countries such as Belgium and Spain are planning to phase out nuclear power and transition to renewable energy sources. Belgium aims to shut down all nuclear plants by 2025, whereas Spain plans to decommission its reactors over the next decade.

Other Member states, such as Bulgaria, Czechia, Finland, and France, are committed to maintaining or expanding their nuclear capacity. Bulgaria considers nuclear energy




Nuclear reactors in Europe 2023, by status




EU's electricity mix: share of electricity production by source in 2023

essential for a stable, low-carbon supply, whereas Czechia and Finland foresee significant increases in nuclear power. France supports both the continued operation of existing reactors and construction of new reactors.

Eastern European countries, including Hungary, Poland, Romania, and Slovakia, emphasise the importance of nuclear energy in future energy strategies. Hungary and Poland are expanding their nuclear capabilities; Romania plans new reactors by 2050; and Slovakia has projects extending to 2040.

In the Nordic region, Sweden plans to maintain its nuclear capacity until at least 2040, while Estonia is exploring nuclear options post-2030. The Netherlands also sees nuclear power as a complement to renewables, planning to extend the life of its Borssele plant and explore new projects.

As of 2023, the EU's electricity consumption comprises a significant portion of its low-carbon energy sources. More than half of the electricity (approximately 67%) comes from clean energy sources, including nuclear, wind, hydropower, solar, geothermal, and biofuels. Of these, nuclear energy makes up nearly a quarter of the total consumption at around 23%, while wind contributes approximately 17%. Hydropower and solar energy account for approximately 12% and 9%, respectively.

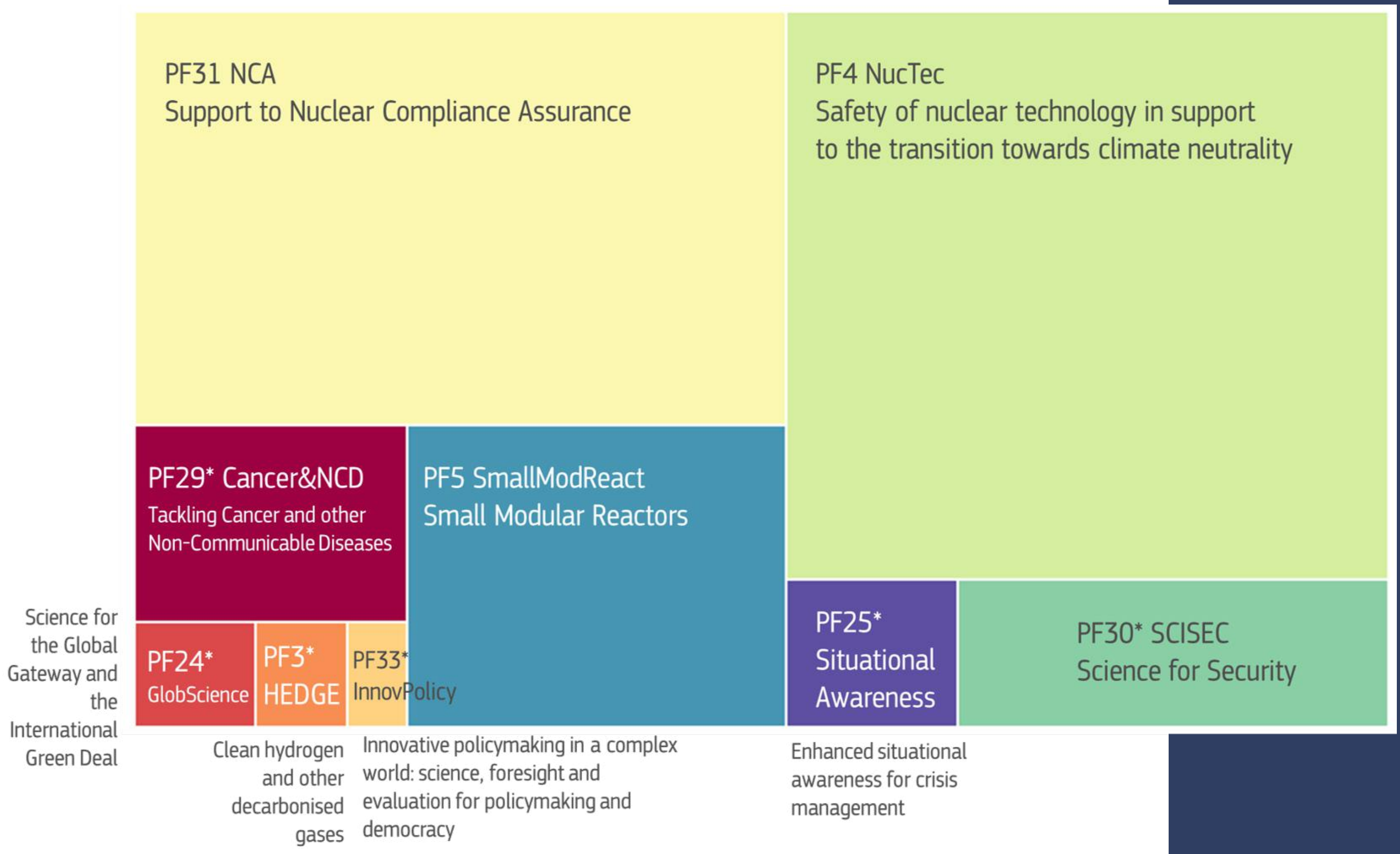
"In 2023, the EU achieved a significant milestone in the electricity sector as more than two-thirds of the electricity generated came from clean sources for the first time."

On the other hand, fossil fuels still play a considerable role, providing approximately 32% of electricity, with gas and coal being the primary contributors, each supplying approximately 17% and 13%, respectively. Oil is barely a factor, generating just over 1% of the electricity.

Nuclear power continues to be the EU's largest source of electricity. Nuclear generation recovered slightly from the 30-year low in 2022, as a rebound in France more than offset the fall from Germany's nuclear exit. Furthermore, the nuclear generation hit new records in Finland and Slovakia as new plants came online. Nuclear energy has regained popularity. The role of nuclear energy is at the centre of the debate on Europe's independence and energy security after Russia's invasion of Ukraine.

Member States target net zero, and a desire for greater energy security has led to a surge in new projects. According to the International Energy Agency (IEA), global nuclear power capacity would need to more than double to 916 GW by 2050 to meet the internationally agreed goal of net zero carbon emissions at that time.

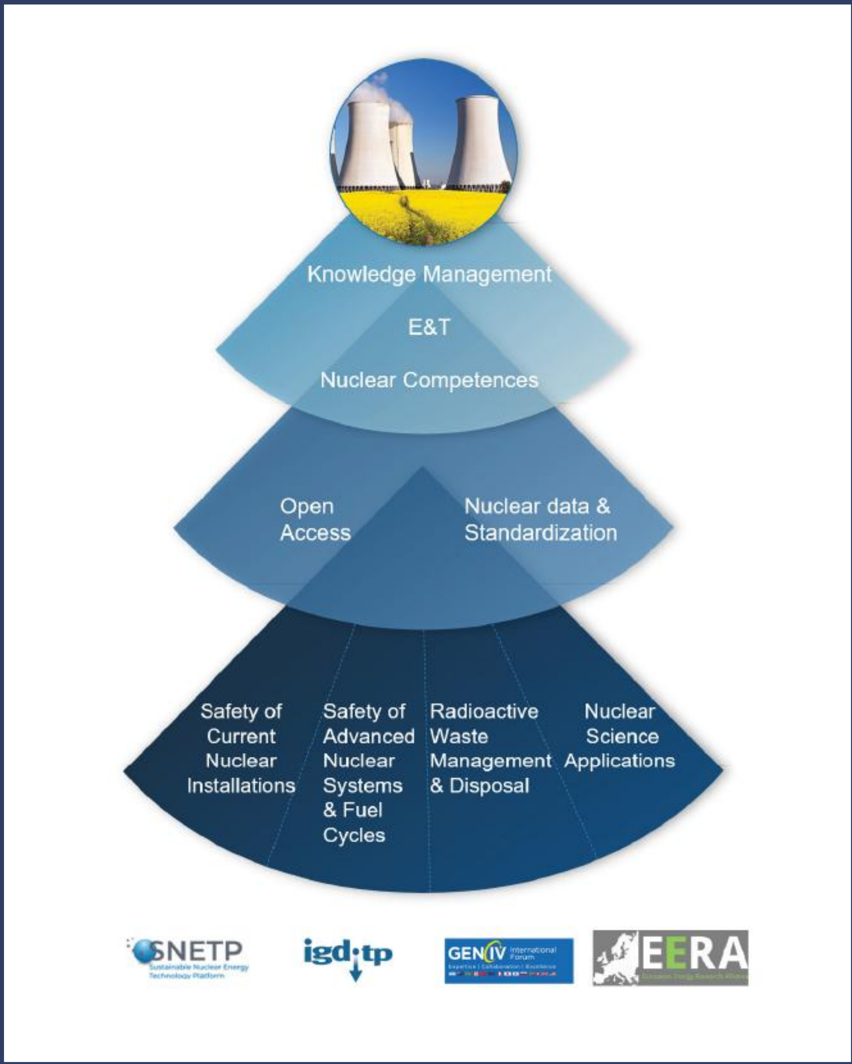
Overview of Euratom activities in the JRC Directorate G
Nuclear Safety and Security work programme for 2023-2024



# PF4 at a glance

# 02

Scientific Portfolio 4 (PF4) four main research pillars, supported by nuclear data, standardisation, open-access schemes, and related cross-cutting activities.




A paradigm change and new drivers for the nuclear sector emerge due to the new geopolitical context (political, economic, and social challenges) and the need to ensure the EU's strategic energy autonomy and green transition. The energy crisis and increased need to rely on all domestic energy sources have triggered a renewed interest in nuclear energy and a change in some Member States' outlook on nuclear power.

Article 194 of the EU Treaty states that the **energy mix** is a national competence, provided that European goals are met. Nuclear energy can contribue to achieving the bloc's net-zero emissions goal as a low-carbon technology by applying the principle of technology neutrality.

The Taxonomy Complementary Delegated Act (CDA) on climate change mitigation and adaptation, in force since January 2023, includes selected nuclear activities as transitional technologies that contribute to achieving a climate-neutral economy but are subject to strict conditions.

Human resources allocated by project, unit, and activities in Portfolio 4.

# “Portfolio 4 R&D preserves short- and long-term **nuclear competencies** for the EU’s energy transition and net zero goals by 2050”

The JRC aligns its work with Member States and/or international organisations’ research programmes. It contributes to technology platforms (TP), such as the Sustainable Nuclear Energy Technology Platform (SNETP) and Implementing Geological Disposal Technology Platform (IGDTP), and cooperates with the European Energy Research Alliance (EERA) and GEN IV International Forum (GIF).

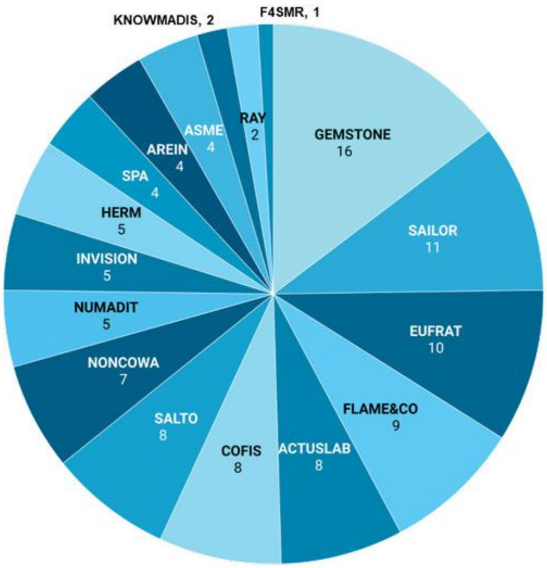
The JRC works closely with R&D entities, universities, utilities/licensees, vendors, TSOs, national regulatory authorities, and waste management organisations of EU Member States and international partners, as well as networks and associations. Through its research, the JRC helps both the Commission and Member States implement nuclear safety and waste management regulations and maintain Europe’s autonomy in nuclear technology.

The JRC Dir G work programme for 2023-2024 is distributed across nine portfolios. There are three nuclear portfolios and some activities are integrated into non-nuclear portfolios.

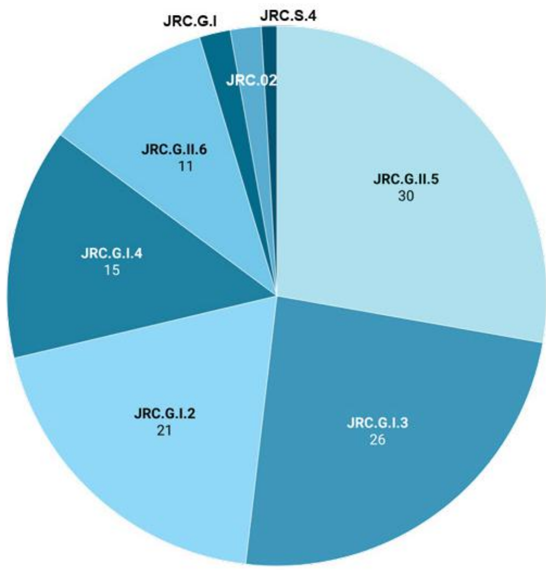
Portfolio 4 is the JRC contribution to maintaining and developing technological leadership and promoting excellence in nuclear research and innovation, ensuring not only the highest standards of safety but also continuity between short- and long-term research and competences in the context of the energy transition and decarbonisation of the EU economy by 2050.

PF4 is a combination of specialised research infrastructure and advanced nuclear competences applied to the research field of nuclear safety in the nuclear life cycle and non-energy applications of nuclear technologies. These competencies are crucial for maintaining nuclear knowledge at all levels, and ensuring the safe and secure peaceful use of nuclear energy and nuclear technologies.

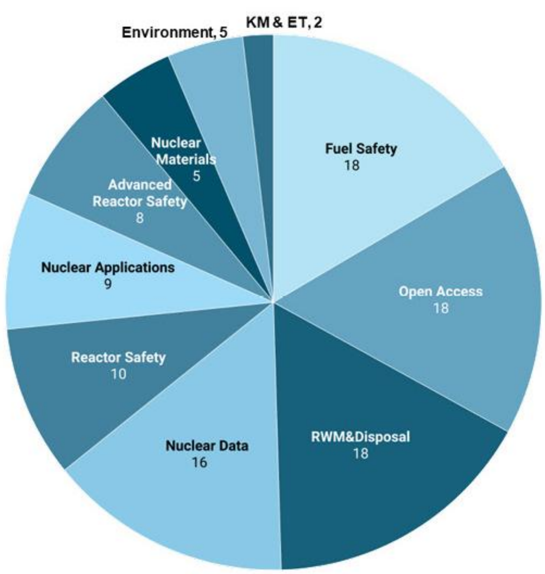
The main activities performed in the Portfolio 4 projects address the nuclear safety of current nuclear power plants and innovative designs, including the safety of nuclear fuel, safe management of spent fuel and nuclear waste, and non-power applications, in particular, applications of nuclear science such as space applications and radiation protection. These activities are complemented by nuclear data, standardisation, open access schemes, and related cross-cutting activities such as knowledge management and foresight.




The 17 scientific and cross-cutting projects in Portfolio 4.

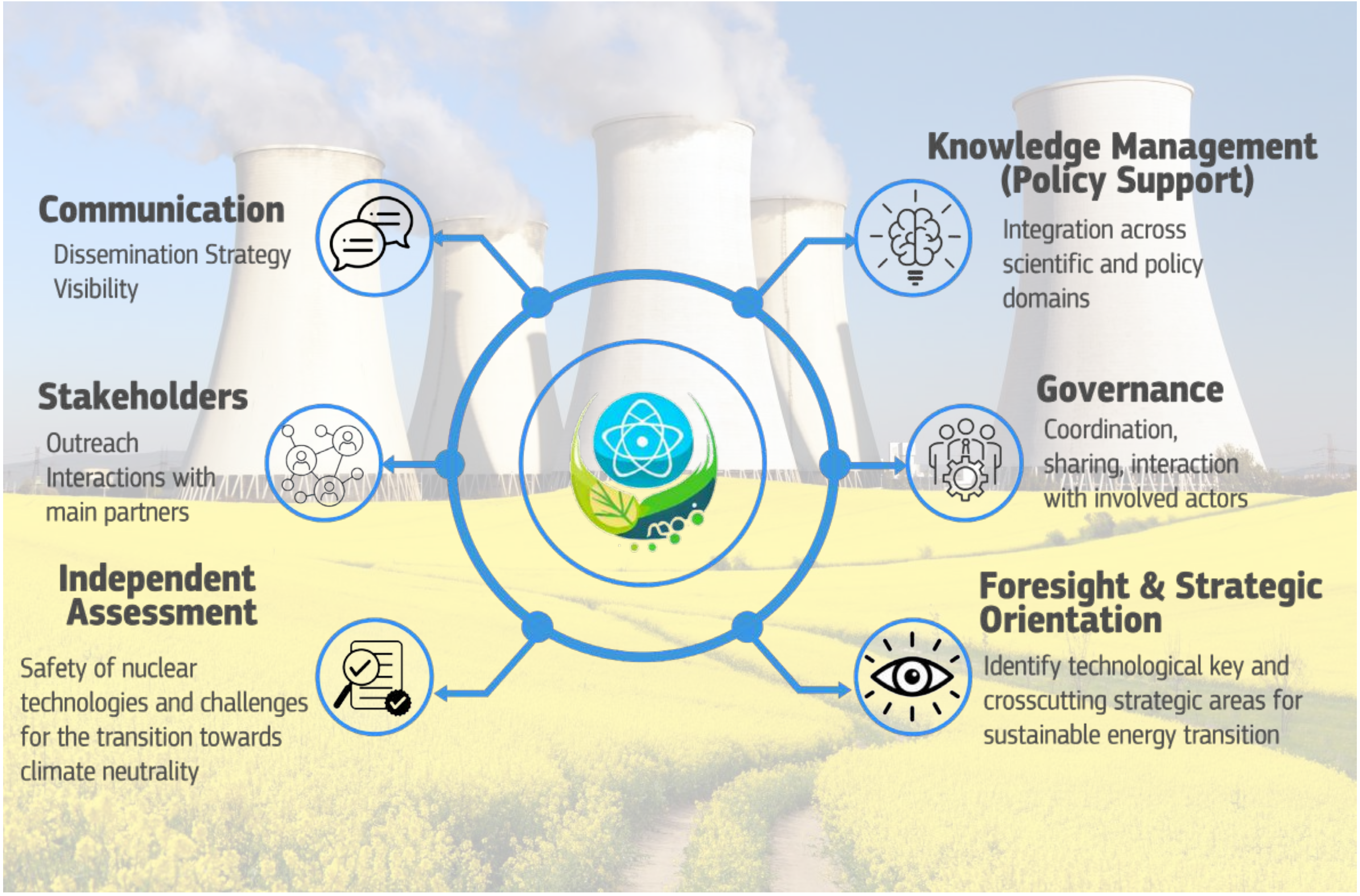



PF 4 integrates human resources allocation from 7 scientific units from Dir G and 1 from Dir S (Innovation in Science and Policymaking).




Human resources allocation by activity. PF 4 represents 108 FTE compiling competences, expertise, and related networking capabilities, covering a significant sector of the nuclear life cycle.

FTE: Full Time Equivalent

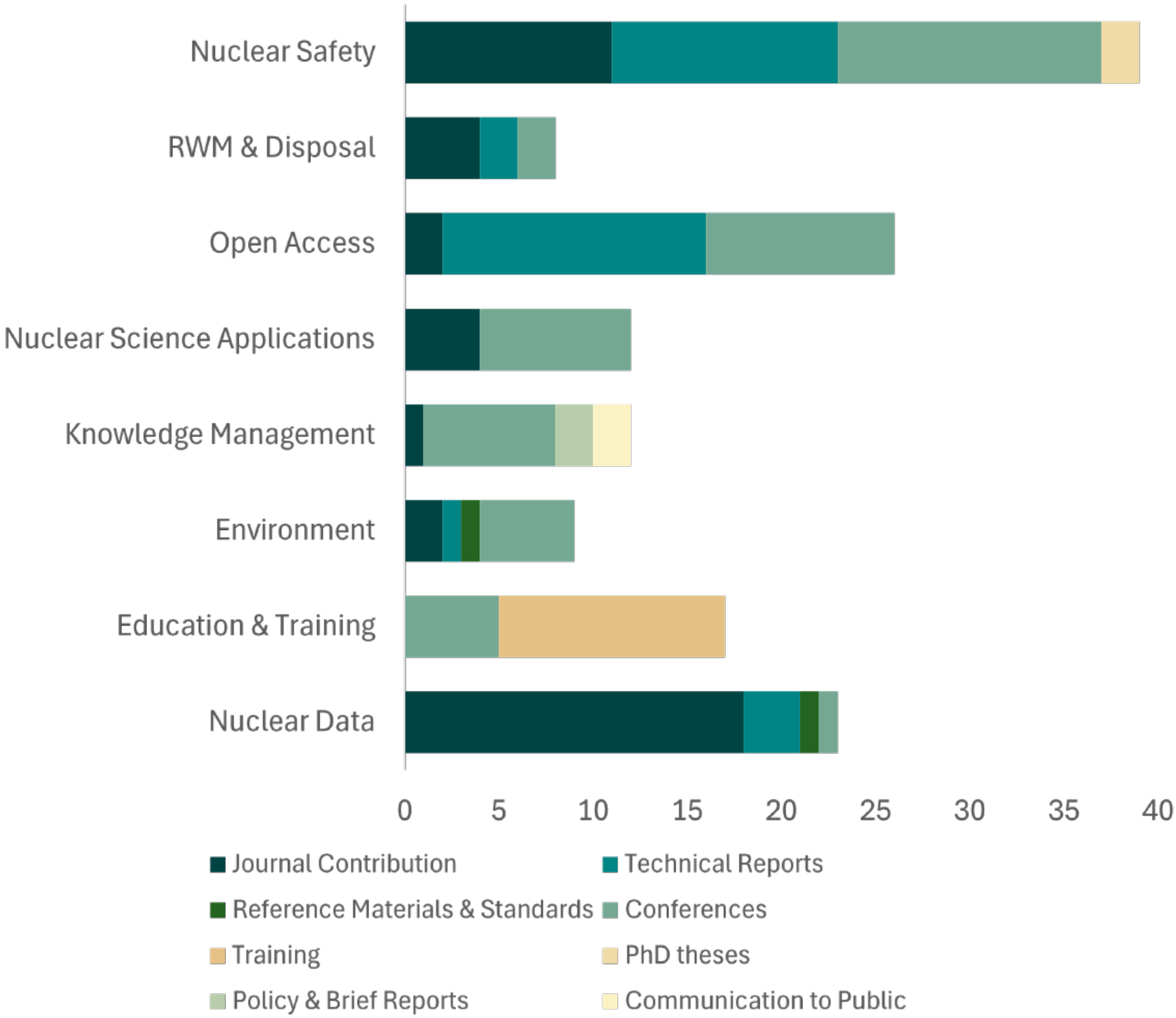



Main functions of the portfolio 4, coordination, integration and communication instruments

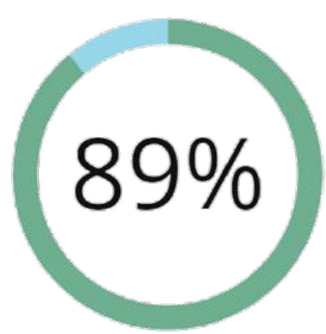
Portfolio 4 brings together scientific disciplines from Dir G to address the common themes and issues. The cross-disciplinary approach aims to create new insights, knowledge, and methods, ensuring better integration across the scientific and policy domains. The main roles of PF4 are to ensure that work under the portfolio is organised and coordinated efficiently, including information sharing, cross-project coordination, and joining the dots between main outputs.

The functions covered by the portfolio include communication and visibility, outreach and stakeholder relations, internal coordination, governance, knowledge management, and foresight.

In 2023, the PF4 projects recorded approximately 150 outputs. Among these, 130 were scientific outputs, including 42 peer-reviewed journal contributions. Approximately 20 belonged to other categories, including policy and brief reports, communication with the public, and training.




## Scientific Output




### Performance Asseessment

The productivity and impact of the PF4 projects in 2023 are depicted in the figure.
Scientific output accounted for 89%.

Current fleet & Advanced nuclear systems

03

# Safety of the nuclear life cycle

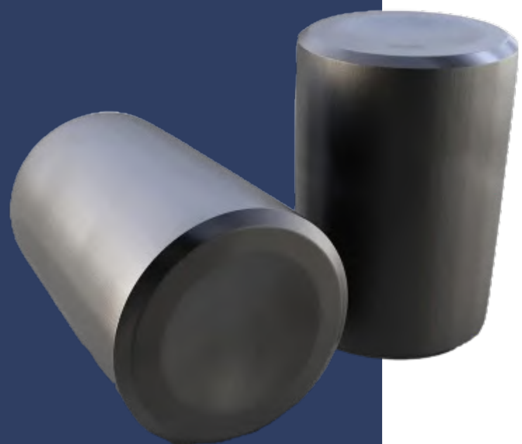
Nuclear power plant cooling towers steaming

JRC nuclear **reactor safety** research is focused on design-basis analysis and beyond design-basis analysis of reactor systems, as well as on the study of materials and components. Many JRC activities in this field are crosscutting, addressing **current light water reactors** (LWR) and future **Generation IV systems**. The JRC leverages synergy with **irradiation experiments** performed in the High Flux Reactor (HFR) in Petten and, in the future, in the Jules Horowitz Reactor in Cadarache, France.

Laboratory tests enable JRC researchers to predict the potential degradation of reactor components exposed to a combination of factors such as the reactor coolant environment, neutron irradiation, and mechanical load. By utilising analytical and numerical simulations, the JRC can assess the impact of ageing on plant life management and safety characteristics, which are critical for the **long-term operation** (LTO) of current reactors pursued by various Member States. The experimental data compiled by the JRC, and its Member State partners are stored in the JRC material database MatDB, which forms the basis for lifetime assessment in service inspections, codes, and standards.

The JRC's **nuclear fuel safety** research provides tools and data for the analysis of **fuel behaviour** in reactors during normal operation and design-based incidents, as well as reference data on the high-temperature behaviour of nuclear fuel. This research covers numerous projects addressing fuels for various reactor types, including **advanced technological fuel (ATF)** for light-water reactors, mixed oxide fuel for **sodium-cooled and liquid metal-cooled fast reactors** (SFR and LFR), and liquid fuel for molten salt reactors (MSR). The JRC primarily contributes to experimental studies using its nuclear infrastructure and instruments, as well as, to a lesser extent, via the TRANSURANUS code network.

Additionally, fuel safety research is included in collaborative research agreements with Member States' research bodies and academic partners such as CEA, NRG, and SCK CEN. The JRC trains young scientists and staff from technical support organisations, research organisations, universities, and industries.



View of two $UO_2$ fuel pellets

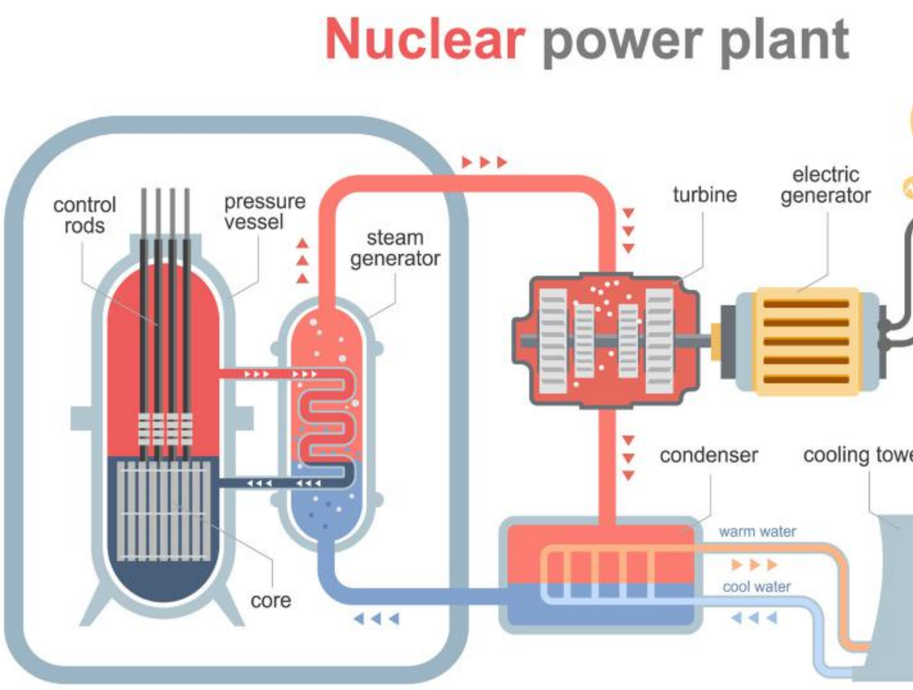
Blue glow in the water of a powered nuclear reactor core caused by Cherenkov radiation

# Safety and Long Term Op Current Reactors

**Life extension** to 50 or 60 years (LTO) for currently operating nuclear power plants (NPPs) is a common practice in European countries with established nuclear programmes that have decided to maintain nuclear power generation in their energy mix. LTO is a means of achieving **intermediate decarbonisation targets**. NPP operators make continuous efforts to refurbish and modernise their NPPs, including the complete replacement of structures, systems, and components (SSCs), to meet stringent regulatory requirements on plant safety and to improve plant performance and economics.

**Emergency response** procedures to mitigate the consequences of design extension conditions (DEC = accident conditions) are updated continuously. NPP operators have implemented **ageing management programmes** (AMP) to mitigate the degradation of passive SSCs and **in-service inspection (**ISI) procedures to detect flaws in SSCs at an early stage. AMPs and ISI are continuously improved based on the underlying R&D, and new ones are developed and implemented, if needed. NPP operators perform preventive maintenance of active SSCs to maintain their functionality and shape.

Schematic diagram of a light water reactor



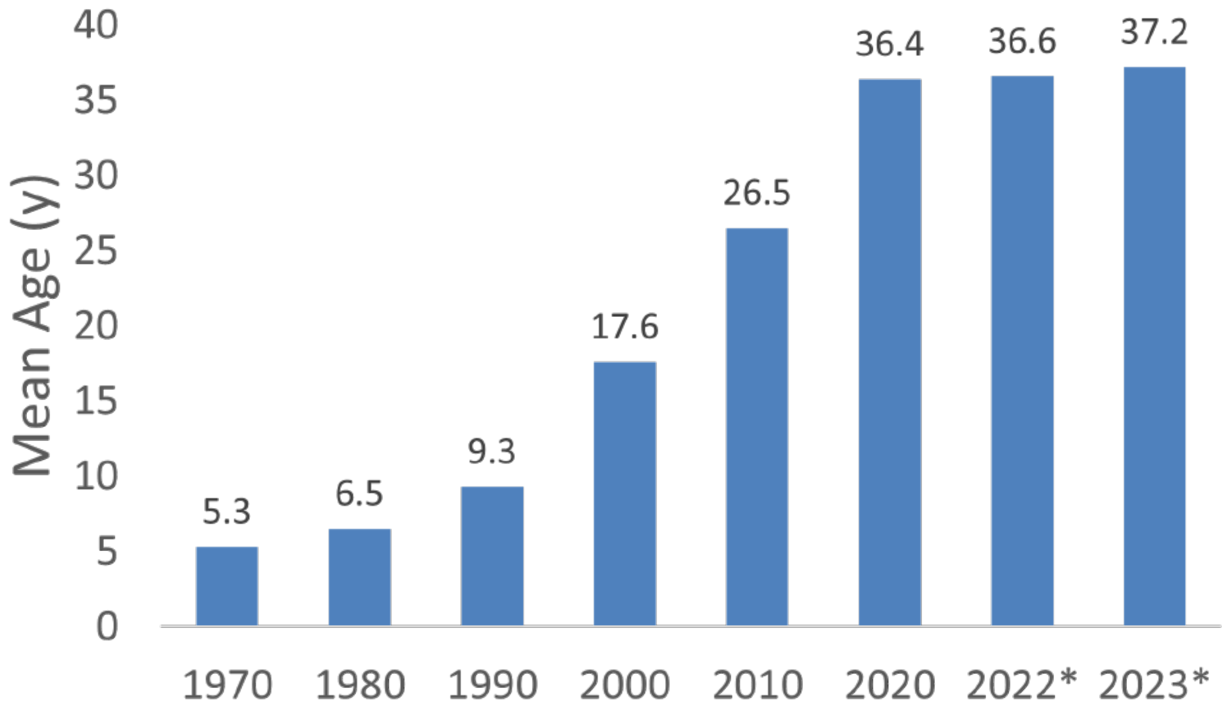
# eration (LTO) of

Cruas, France -  View on the nuclear power plant station Cruas-Meysse


JRC activities contribute:

- to improve the understanding of the degradation mechanisms of passive structures, systems, and components (SSCs), particularly metallic components, of current light water reactors (LWRs) and to identify mitigation measures;
- to the further evolution of integrity and lifetime assessment procedures, nuclear codes, and standards for safety-classified SSCs;
- to the evolution and harmonisation of practices related to in-service inspection and equipment qualification for SSCs;
- to reactor safety assessment, including the development of computational tools, design extension conditions (DEC = accident conditions), and source term uncertainty analyses;
- to improve the emergency preparedness measures for current LWRs.

**Mean age of nuclear reactor fleet in the European Union in selected years from 1970 to 2023**




Sources: Statista and WNISR2023

In 2023, the mean age of the European Union nuclear fleet was 37.2 years. As of July 2023, 87 of the 100 nuclear reactors in the EU were older than 31 years.

60 % of Generation II and III reactors in Europe have almost reached their **nominal target lifetimes**. One of the main issues preventing LTO is the **embrittlement** of the Reactor Pressure Vessel (RPV), a non-replaceable component whose mechanical properties degrade over time. RPVs must be able to safely withstand both emergency and normal conditions for extended periods of operation. Together with 17 EU partners, the JRC is implementing the H2020 STRUMAT-LTO project, aiming to fill research gaps in nuclear reactor **ageing mechanisms**, specifically focusing on Reactor Pressure Vessel (RPV) embrittlement. JRC performed testing on previously irradiated materials and contributed to the validation of embrittlement trend equations as well as master curve approaches.

The prediction of the lifetimes of nuclear plant components when subjected to environmental assisted fatigue loading is the overall objective of the Euratom project INCEFA-SCALE. The consortium involved 16 partners, and the JRC contributed to mechanical uniaxial tests and the management of the engineering database MatDB.

The European Network for **Inspection and Qualification (ENIQ)** is a utility-driven network working mainly in the areas of qualification of non-destructive testing (NDT) systems and risk-informed in-service inspection (RI-ISI) for nuclear power plants (NPPs). The ENIQ is recognised as one of the main contributors to today's global qualification guidelines for in-service inspection.

# Euratom H2020 MUSA project

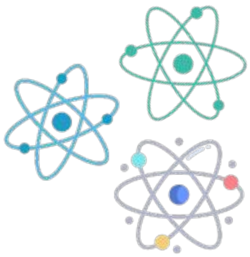
The MUSA project aims to quantify the uncertainty in **severe accidents codes** when modelling accident scenarios to predict the radiological source term. Uncertainty Quantification (UQ) methodologies are being applied to initial and boundary conditions, model parameters, and even accident management measures. Source term-related Figures of Merit (FOMs) were set for each scenario in which the Best Estimate Plus **Uncertainties** (BEPU) was applied. The MUSA project ended on May 2023.

The JRC contributes to uncertainty quantification in the analysis and management of reactor accidents.

MANAGEMENT AND UNCERTAINTIES OF SEVERE ACCIDENTS


JRC published new technical reports, position papers, and a proposal for a roadmap for risk-informed in-service inspection development (ENIQ report 69).

JRC participated in the organisation of the international conference of **Non-destructive Examination**, NDE in Nuclear 2023, organised by SNETP and held in Sheffield (UK) from June 27-29, 2023. JRC staff serving in the SNETP Secretariat were directly involved in the organisation of the conference, chairing both the conference's program committee and the conference's organising committee. NDE professionals from nuclear utilities, inspection vendors, inspection equipment manufacturers, qualification bodies, research laboratories, and other nuclear stakeholders have discussed the latest advancements in R&D and application of NDE technologies for the commercial nuclear industry. A total of 174 conference attendees participated, delivering three keynote speeches and 76 technical presentations from 17 countries. Presentations focused on innovative topics, such as NDE 4.0, analysis of NDE data using artificial intelligence or machine learning, and advanced manufacturing and NDE. Inspection-related case studies in operating plants and common topics on regulatory and code issues, harmonisation, personnel, and human factors, including NDE personnel training and certification, were also discussed. The conference also involved a technical exhibition and showcase at the Nuclear Advanced Manufacturing Research Center (NAMRC). Eighteen inspection vendor companies displayed their NDE technologies and services during exhibitions.



Damage profile for 5 MeV ion ($Fe^{2+}$) irradiation of pure iron G379

# Reactor structural components radiation stability studies

During reactor operation, the generated high-energy neutrons interact with materials in the reactor core, potentially causing structural damage. Prolonged neutron bombardment can make reactor materials brittle, especially in the reactor pressure vessel, reducing the structural integrity over time, whereas swelling and creep mechanisms induced by atomic displacements in materials can affect the mechanical stability and lifetime of reactor components. The evaluation of the effects of these phenomena is crucial for determining the operational safety limits, lifespan, and life extension of nuclear facilities.

Ion irradiation of structural materials in nuclear reactors is a widely used technique to simulate neutron irradiation. During the design phase of irradiation experiments, Monte Carlo transport codes are often employed to quantify radiation exposure by estimating the displacements per atom (dpa) quantity. The JRC conducted benchmarking of multi-purpose Monte Carlo codes (CERN-FLUKA.2, coupled with the Flair 2.2 interface, MCNP6.1, PHITS 2.88, and SRIM) via simulation of irradiation by proton, neutron, and iron ion beams and displacement calculations.

Owing to the shallow penetration depth of charged particles into matter, typically spanning from one to several tens of micrometers, the mechanical properties are anticipated to change within this superficial layer. Consequently, the investigation of ion-induced damage was complemented by micromechanical and surface-sensitive testing methods. Displacement calculation results are obtained in the form of damage profiles and total displacements-energy trends

Regarding proton irradiation, the damage profile simulations showed agreement in the overall trend between all the codes, but significant differences were observed in the peak heights and, consequently, the integral areas representing the total number of displacements (per atom). Differences in computing the displacements per ion, and consequently, the total dpa amount, were observed over the entire simulated energy spectrum. The main parameter affecting the damage profiles, but not the total dpa estimates, appears to be the density.

Heavy iron ion simulations yielded damage profiles characterised by shapes and peaks with significant disagreements among the codes. On the other hand, the total amount of displacement per incident particle is very consistent, except for PHITS, over a wide portion of the considered spectrum.

SRIM lacks the capability to simulate nuclear reactions, leading to an underestimation of the displacement per atom (dpa) at energies pertinent to these reactions. However, SRIM incorporates tuning parameters, such as surface and lattice binding energy, which are not present in other codes. These parameters enable more precise estimates of displacements. MCNP relies on external cross sections for displacement calculations involving ions, restricting its applicability to the data provided by other studies. The energy straggling implementation in FLUKA for heavy ion simulations appears to be less refined compared to other codes, particularly at the energies selected for this study. The PHITS code exhibits a tendency to underestimate displacement generation when subjected to impinging Fe ions with energies exceeding 5 MeV.

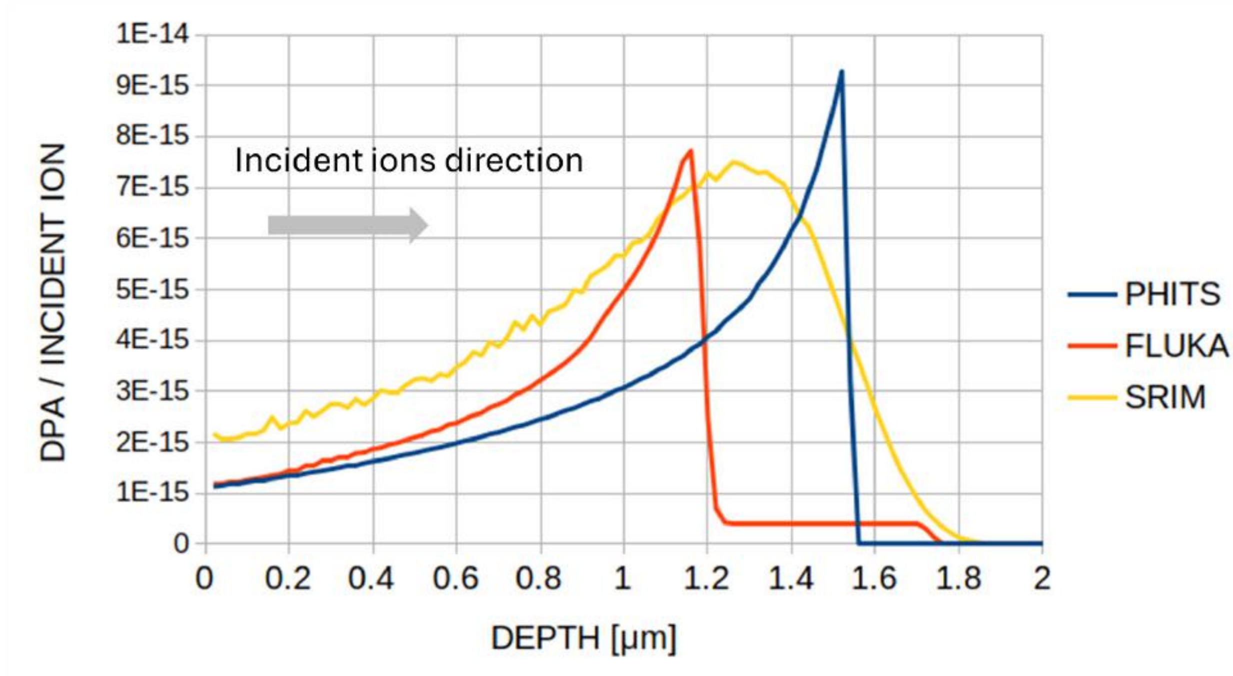
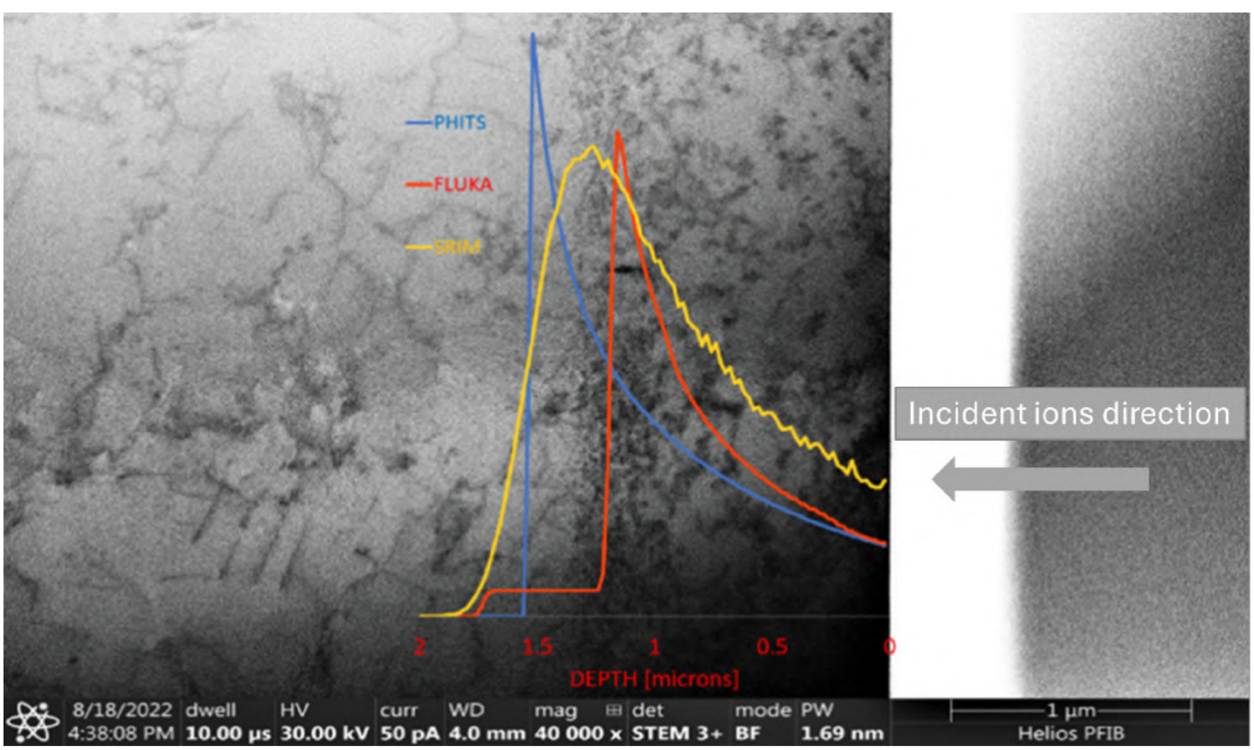
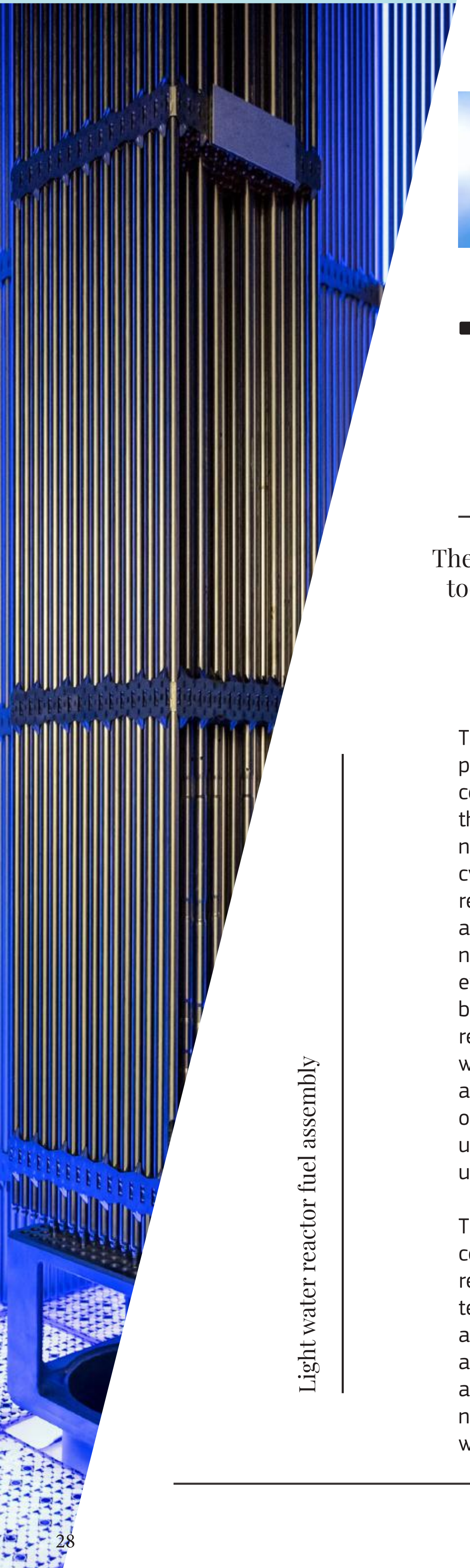



Image of a specimen irradiated with Fe ion overlapped with simulated damage profiles. A darker stripe appears to be in the proximity of the damage peak foreseen by the codes





Light water reactor fuel assembly

# TRANSURANUS

## FUEL PERFORMANCE CODE

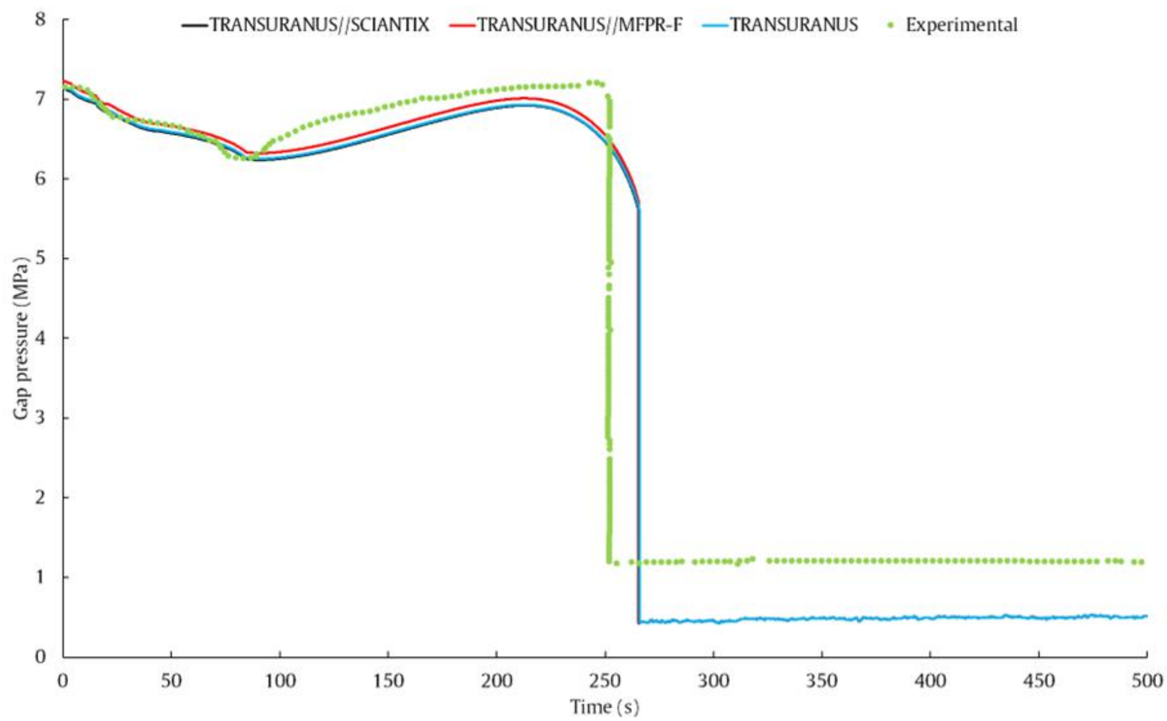
The TRANSURANUS fuel performance code is a comprehensive tool used for the thermal, mechanical, and neutron-physical analysis of cylindrical fuel rods in nuclear reactors.

The TRANSURANUS fuel performance code is a comprehensive tool used for the thermal, mechanical, and neutron-physical analyses of cylindrical fuel rods in nuclear reactors. It is designed to handle a variety of conditions, including normal operation, off-normal events, and accidents, across both thermal and fast spectrum reactors. The code is equipped with a built-in material data bank and can operate in deterministic or statistical modes, which is useful for assessing uncertainties using Monte Carlo techniques.

The TRANSURANUS fuel rod code is used by universities, research organisations, industry, technical safety organisations, and regulatory bodies in the EU and worldwide for the safety assessment of cylindrical nuclear fuel rods in current as well as future reactor types.

The JRC organised a one-week training course on the TRANSURANUS code in Karlsruhe, providing a theoretical foundation for nuclear fuel behaviour in reactors. The course covered how to prepare and use TRANSURANUS for fuel performance analysis, focusing on the thermal and mechanical behaviour of nuclear fuel and gaseous fission products. Additionally, the course introduced the SCIANTIX code from POLIMI and MFPR-F code from IRSN.

The EU H2020 R2CA project (Reduction of Radiological Consequences of design basis and extension Accidents) develops new calculation methodologies and updated computer codes (integrating the evaluation of uncertainty) to produce more realistic evaluations of radioactive release resulting from loss-of-coolant accidents (LOCA) or steam generator tube rupture (SGTR)

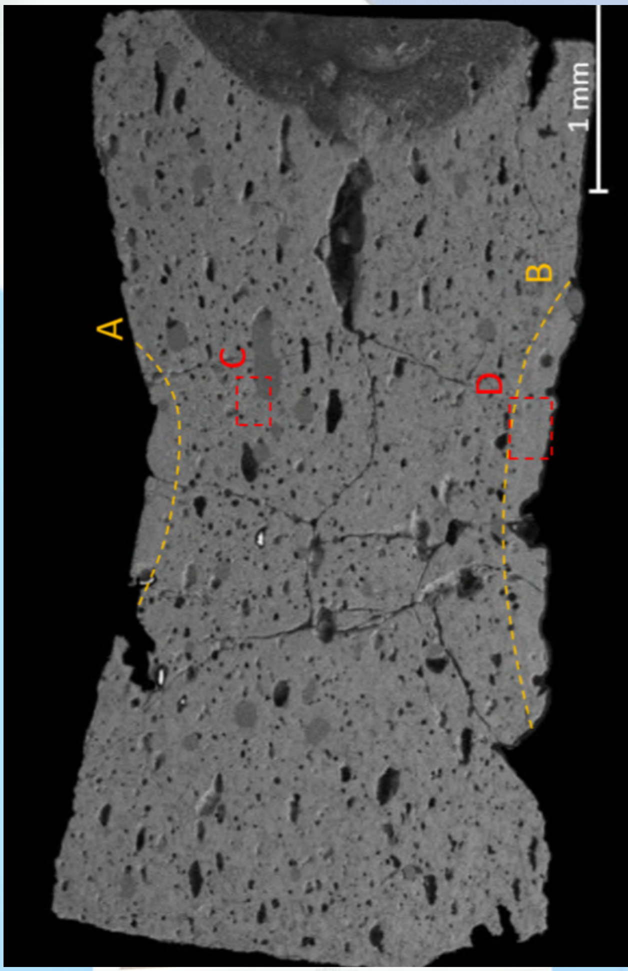



Comparison of experimental fuel rod internal pressure after the blowdown of the IFA-650.10 test, and calculations of the different TRANSURANUS versions

accidents. In most current nuclear safety studies, radiological consequences are assessed based on 'conservative' scenarios and assumptions that differ from one country to another. The new design methodologies developed will be harmonised and tested on different types of Generation II and III reactors to improve accident management and propose new reactor system instrumentation, thereby improving facility safety.

The JRC extended the scope of the fuel rod simulations to radioactive fission products in the context of the R2CA project with several partners. Among the applications of the multiscale modelling approach in nuclear fuel rod performance, the coupling of integral thermo-mechanical fuel performance codes with lower-length mesoscale modules is of great interest. This strategy allows to overcome correlation-based approaches using mechanistic approaches and to test their application under accidental conditions. JRC explored the coupling between the TRANSURANUS fuel performance code and two mesoscale modules for fission gas/product behaviour: MFPR-F and SCIANTIX. These modules, coupled within TRANSURANUS, were assessed against the Halden IFA-650.10 loss-of-coolant accident test to analyse their overall impact and highlight future developments toward the mechanistic modelling of fission gas during accident scenarios. The calculations of the three versions of TRANSURANUS qualitatively reproduced the same behaviour for the fuel rod inner pressure. In particular, the codes follow the experimental behaviour with good accuracy until 100 s. The JRC staff contributed to the summer school of the R2CA project in Bologna, Italy (July 4-6, 2023). Approximately 60 participants attended, mainly master's and PhD students, young researchers, and engineers involved in nuclear energy and reactor safety analyses. Along the school, the main safety aspects related to design basis accidents (DBA) and design extension conditions (DEC-A) of LOCA and SGTR accidents were discussed, focusing on the phenomenology, available experimental knowledge, and current numerical modelling. The main advancements within the R2CA project served as a background to show the current state of art and the new ideas. The school targeted fundamental knowledge, current nuclear safety-best practices, and innovation. In addition, a panel of topics of interest for future nuclear safety research is presented.

# Validation of the international TAF-ID database on nuclear materials




Cross-section of a UO2-corium sample

Detailed modelling of the fuel-cladding system is of major importance in several studies related to safety improvements, lifetime extension of Generation II and III reactors, and the design of advanced Generation IV systems. The use of **thermodynamic data** is needed for various analyses involving nuclear fuel: design of the fuel element, modelling of the fuel-cladding system under normal conditions in performance codes, analysis of fuel and cladding behaviour under severe accident conditions (pre-and post-fuel melting), and the interaction of corium with the vessel, sacrificial materials (in-vessel), and concrete (ex-vessel).

The Thermodynamics of Advanced Fuels - International Database (TAF-ID) project aims to develop a thermodynamic database as a computational tool for understanding advanced fuel materials. This thermodynamic database allows for the prediction of the **phase diagrams and thermodynamic properties of the phases**.

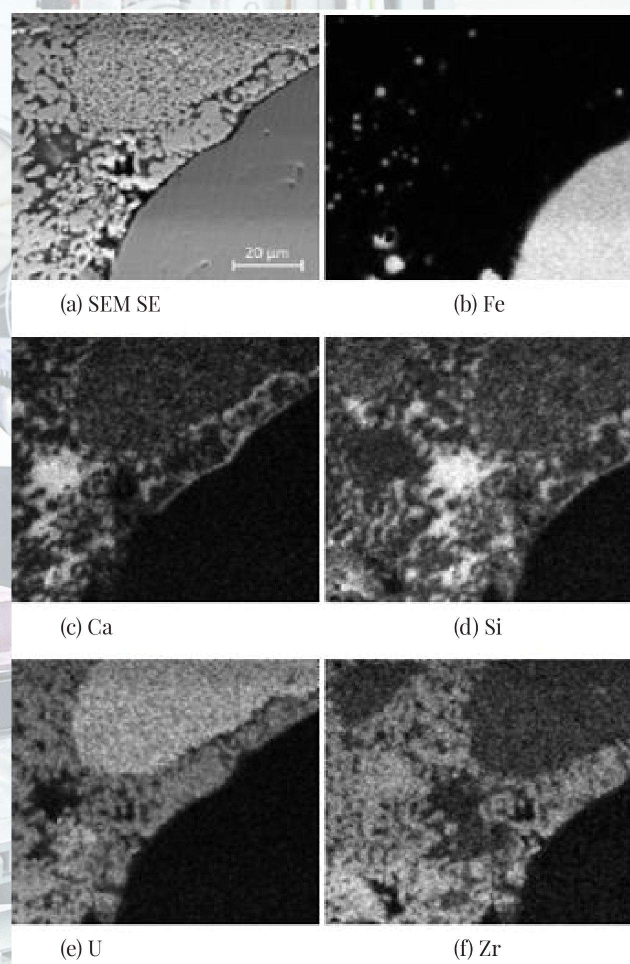
Upon request of the **TAF-ID** consortia managed by the NEA-OECD organisation, JRC performed a series of targeted experiments with radioactive samples to validate two specific systems. The first system was representative of an ex-vessel corium, consisting of nuclear fuel, fuel cladding, steel, and concrete representative materials, whereas the second consisted of (U, Pu)$O_2$ (MOX) with lanthanides (2.5. % each of Ce, Gd, La, and Nd). The experimental observations included measuring the liquidus and solidus temperatures, characterisation of the fuel microstructure, phase composition, crystal structure, and measurement of the vapour pressure of the species.

The obtained results were compared with thermodynamic calculations using the TAF-ID database. Excellent agreement was observed between the experimental and calculated results for the $UO_2$-corium system, particularly for the liquidus and solidus temperatures and the composition of the phases.

The results obtained for the MOX-corium system were not fully conclusive due to experimental challenges. However, they suggested that some thermodynamic models should be reviewed, particularly those of U-Zr-O and U-Pu-Zr-O in the hypostoichiometric region. Regarding the MOX-Lanthanide system, evidence of silicon contamination was observed, which led to the formation of a Si-, Pu-, and lanthanide-rich phase in a ratio consistent with $M_2SiO_4$. Although significant differences were observed between the experimental results and thermodynamic calculations owing to this contamination, the miscibility gap in the system was confirmed experimentally. In addition, this contamination has allowed the identification of important knowledge gaps in the database, which will lead to further improvements.

The validated database can further predict which volatile fission products might escape from such materials and provide key data input for further assessments of radiological consequences on the environment. The **validation of the database is key** for its use by researchers, industries, and licencing authorities, as it provides proof of reliability.

Fe, Ca, Si, U, and Zr X-ray maps acquired on an as-sintered $UO_2$-corium sample

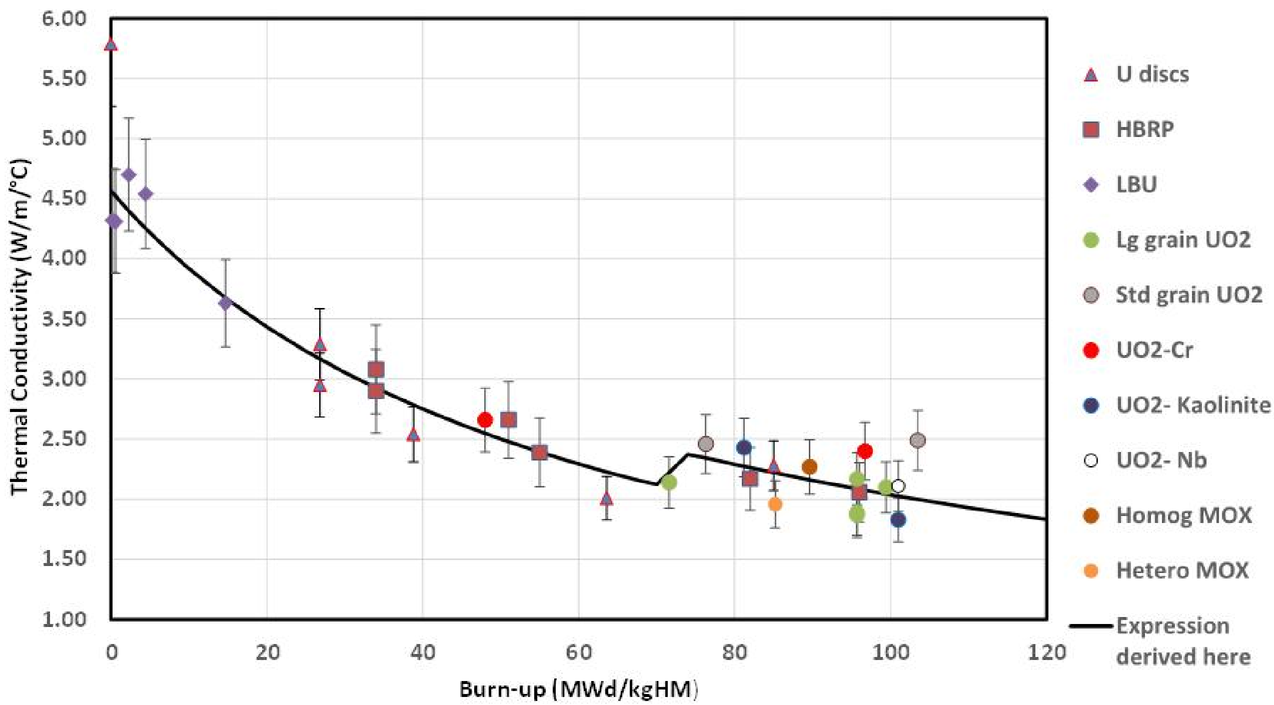



(a) SEM SE (b) Fe

(c) Ca (d) Si

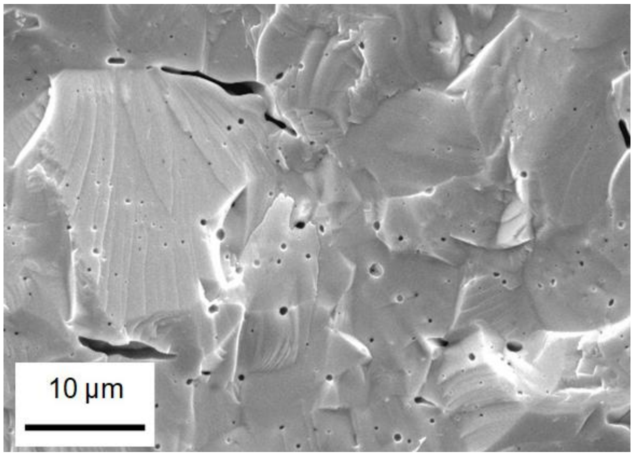
(e) U (f) Zr

Evolution of thermal conductivity at 247° C of $UO_2$, of fuel containing additives and of MOX versus burnup

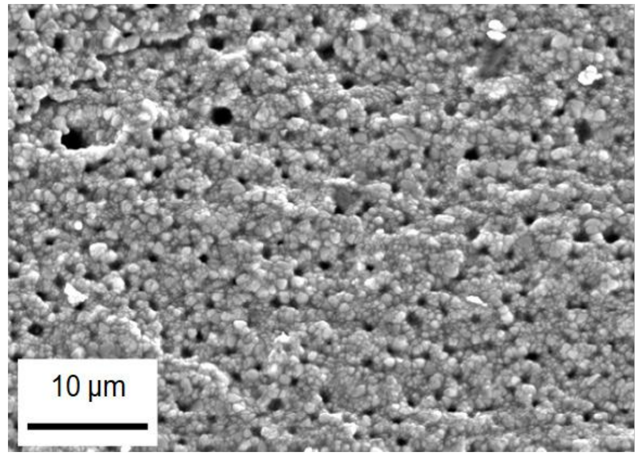



# Effect of burnup on the thermal conductivity of light water reactor fuels

The JRC contributes to improving the **safety assessment of fuels and materials** for the current Light Water Reactor (LWR) fleet in the European Union. This work is performed through collaborations with national Technical Support Organisations (TSOs), industries, and leading research entities in support to Member States. Research needs involve assessing the properties, compatibility, and in-pile performance of LWR fuel, including MOX, additive fuels, and advanced technological fuels and claddings. This includes measuring the **thermal and mechanical properties** of irradiated fuels and claddings. Reliable prediction of the local temperature and radial temperature gradient within the fuel rods is essential for the safe operation of a nuclear reactor. In this context, the JRC aims to enhance the safety analysis and assessment of LWR **$UO_2$**, **MOX**, **doped**, and **innovative fuels** and **claddings** by expanding the **knowledge base of thermophysical properties** for both fresh and irradiated fuels under normal and severe accident conditions.




Scanning Electron Microscopy (SEM) micrographs showing fuel fracture surfaces of unirradiated $UO_2$ fuel




SEM micrographs showing irradiated $UO_2$ fuel with local burn-up of ~75 GWd/tHM exhibiting the typical HBS morphology

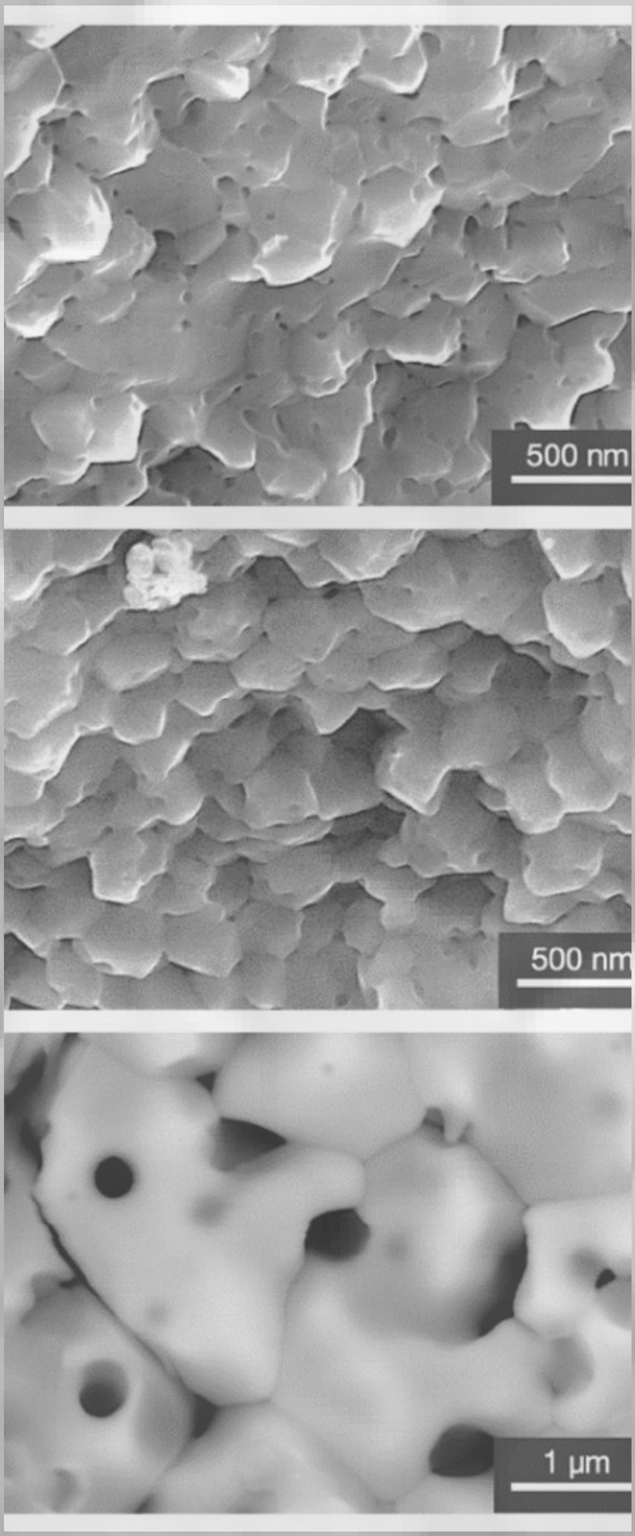
Additionally, the formation of a **High Burnup Structure** (HBS) is possibly the most significant example of restructuring processes affecting commercial nuclear fuel in-pile. The HBS forms at the relatively cold outer rim of the fuel pellet, where the local burnup is 2-3 times higher than the average pellet burnup, under the combined effects of irradiation and thermomechanical conditions determined by the power regime and fuel rod configuration. The main features of the transformation are the subdivision of the original fuel grains into new submicron grains, relocation of the fission gas into newly formed intergranular pores, and absence of large concentrations of extended defects in the fuel matrix inside the subdivided grains.

The characterisation of the newly formed structure and its impact on the thermophysical or mechanical properties is a key requirement to ensure that a high burnup fuel operates within the safety margins.

Research conducted at the JRC with international partners has led to the development of expressions for the degradation of the thermal conductivity in LWR fuels as burn-up levels increase to 120 MWd/kgHM. This study investigated various fuel types, including standard $UO_2$, large grain $UO_2$, and $UO_2$ doped with Gadolinium, Chromium, Niobium, and kaolinite, as well as homogeneous and heterogeneous MOX.

The results indicate that the **thermal conductivity** of the fuel is immediately reduced at the onset of irradiation owing to the radiation damage to the crystal lattice. At high burnups above 70 MWd/kgHM, the thermal conductivity of the matrix in the high burn-up structure increases by 25-30 % due to fuel grain restructuring. However, this increase is partially or completely offset by the decrease in conductivity caused by the porosity of the high burnup structure, which contains fission gas accumulated during the transformation of the microstructure. Below 70 MWd/kgHM, in the absence of the high burnup structure, the conductivity is approximately 15% lower than the currently accepted values. Additionally, the data reveals that the thermal conductivity of $UO_2$ containing 10 wt% $Gd_2O_3$ is significantly lower than that of $UO_2$ at burn-ups below 70 MWd/kgHM.

Once a HBS is formed, its conductivity becomes indistinguishable regardless of whether it is conventional $UO_2$, $UO_2$ with additives, or MOX. A unified description of the dependence of the thermal conductivity on the burnup and irradiation temperature is proposed.




SEM images of the same $UO_2$ sintered sample before the infusion (top), after the infusion but before annealing (middle) and after annealing (bottom)

Accelerated ageing and basic modelling studies are necessary to predict the **long-term behaviour** of stored spent fuels. Property measurements are performed on spent fuel and analogues to determine the long-term evolution and potential effects of **ageing processes** on the mechanical integrity of the spent fuel rod. Spent fuel rod alterations as a function of time and cumulative decay damage and alteration kinetics are monitored at the microstructural level (defects and lattice parameter swelling) and at the macroscopic property level, such as hardness and thermal conductivity.

The results obtained so far show that saturation of macroscopic hardening and thermal conductivity decrease are to be expected after decades or centuries of **storage**, depending on the burnup and composition of the spent fuel. To reproduce the cumulative **decay damage** effects expected after extended storage times within acceptable laboratory timescales, accelerated damage build-up conditions were applied by testing unirradiated (U, Pu) oxide with high specific alpha activity.

Understanding the **helium** behaviour in nuclear fuel is crucial for the long-term evolution of spent fuel under storage conditions. There is still a lack of experimental data, particularly concerning its solubility and diffusivity.

Helium solubility was measured in stoichiometric $UO_2$ and hyper-stoichiometric $UO_{2.13}$ polycrystalline samples in which helium was introduced via infusion by means of all-purpose infusion setup (APIS), an innovative experimental setup. It consists of a laser-heated autoclave, whose peculiarity lies in a custom sample holder designed to minimise thermal gradients both within the sample and between the sample and crucible.

The microstructure of the infused samples is characterised by grains of

# Radiation damage studies: fuels and actinides compounds

different sizes, from a few µm to ~250 nm, representative of HBS, which is significantly lower than the typical grain size of the conventional microstructure (10 µm). The obtained solubility values were consistent between samples belonging to different size groups but were higher than those measured from representative conventional fuel.

This study contributes to the assessment of the effect of grain boundaries and helium behaviour in HBS. The data obtained could be implemented in physics-based models for describing helium behaviour in nuclear fuel, and it could be recommended for better predicting helium mobility in HBS, which is fundamental in fuel performance codes.

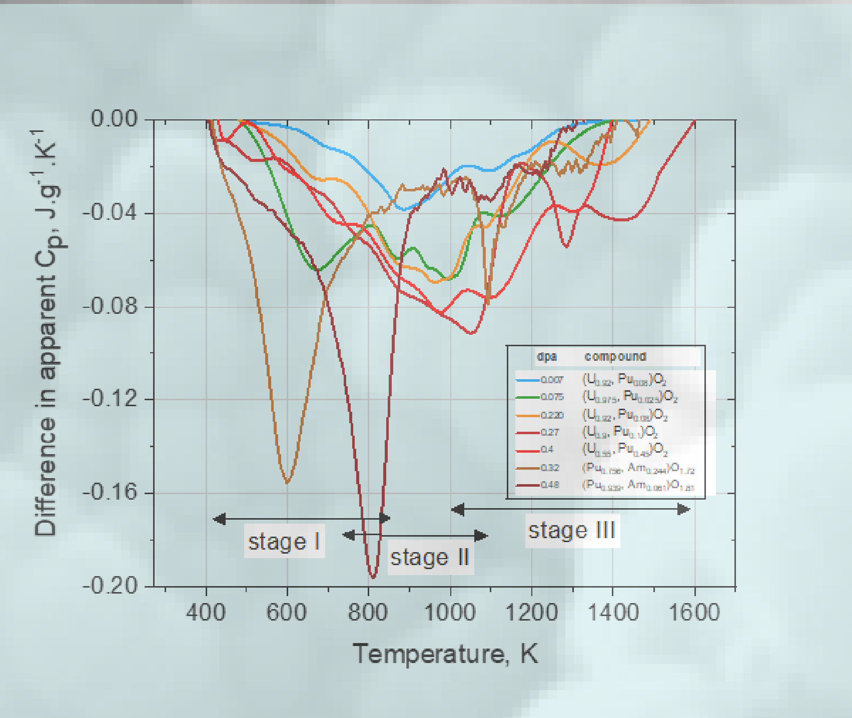
The **heat capacity** of actinide-mixed oxide samples with cumulated alpha-decay damage was measured during thermal annealing. Differential scanning calorimetry (DSC) measurements of samples undergoing alpha-damage showed that annealing of non-equilibrium defects produces measurable heat.

The total energy stored by different defects can also be assessed. It can be shown that the stored energy from primary defects due to alpha damage tends to saturate because of an equilibrium between production and recombination or precipitation into extended defects. The specific temperature for defect recovery depends on the composition, damage level, and stoichiometry, but three temperature ranges can be described for oxygen (I), cation point defects (II), and extended defect recovery (III). Under **wet storage** conditions, there should be no damage recovery, and it is expected that oxygen defects may recover under **dry storage** conditions.

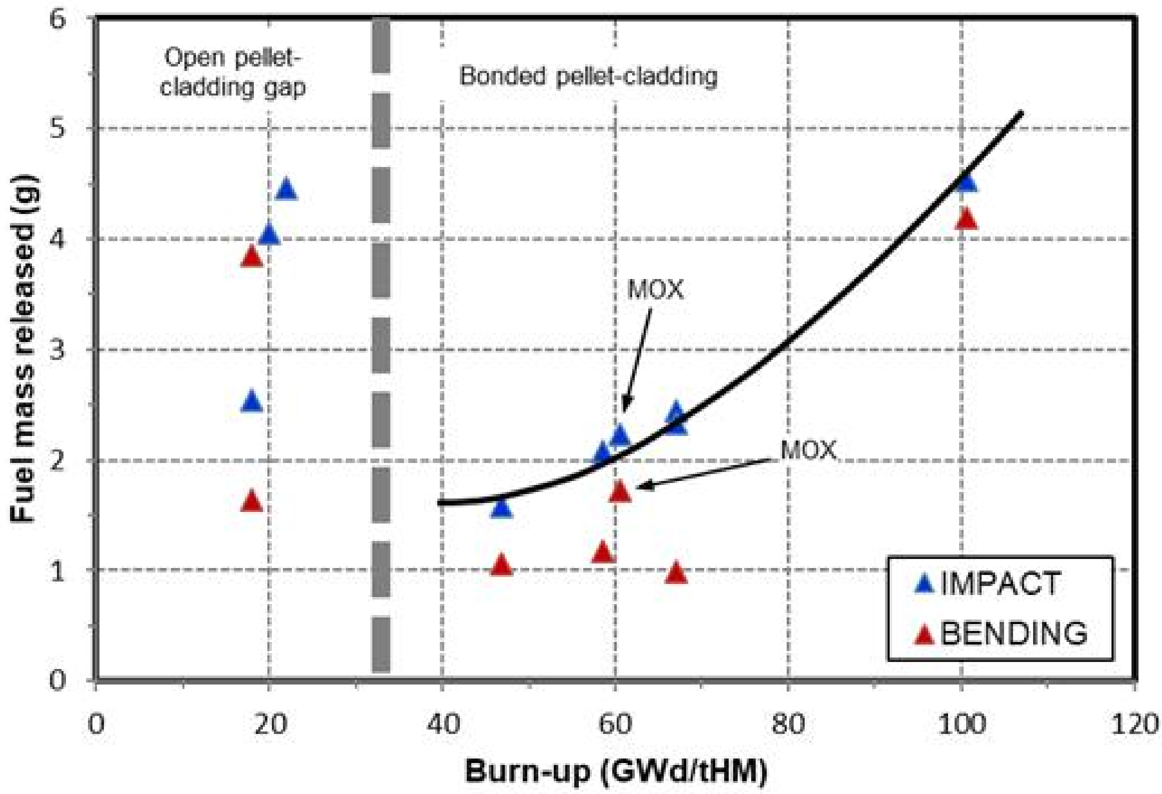
These results provide valuable information on the evolution of the spent fuel state under interim and final storage conditions. Indeed, the stored energy in spent fuels can be expected to increase during the **disposal timeframe**, potentially leading to changes in properties.

| Stage | T(K) | Mechanisms | Engineering temperatures |
|---|---|---|---|
| I | 400-800 | $O_i$ migration, $U_i$ | Wet storage clad. max 473 K<br>Dry storage clad. max 673 K |
| II | 700-1100 | $U_v$, $Pu_v$ migration<br>$O_v$ migration | Fuel operation in LWR |
| III | ≥1000 | Helium desorption from extended defects | Fuel operation in FR |

Apparent Cp* obtained by DSC for seven selected samples representing different compositions, damages, and stoichiometries



Fuel mass released during impact and bending tests as a function of fuel burn-up.
All tests carried out at JRC HC-KA facility

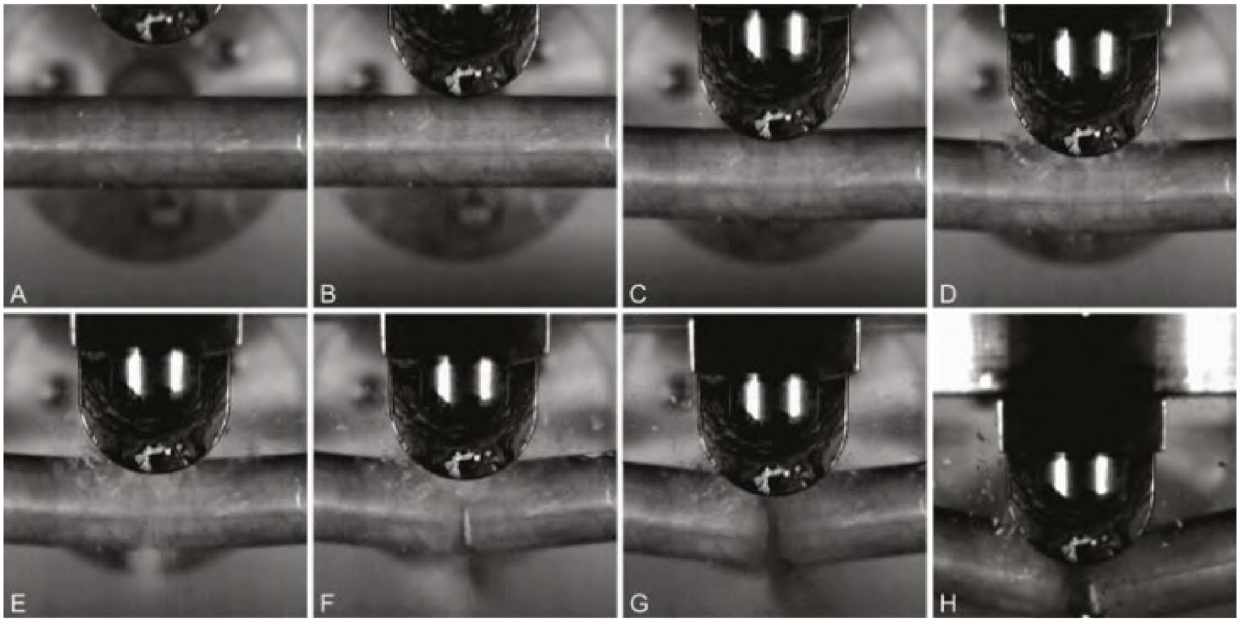



# Safety of interim storage: analysis of spent nuclear fuel rods under accidental loading conditions

In several Member States that make use of nuclear energy, the duration of the **interim storage** of **spent nuclear fuel (SNF)** may be extended up to 100 years and beyond, depending on the timeframe by which deep geological repositories will be constructed and commissioned. This issue extends beyond the present generation. The needs of future generations must be considered by ensuring the availability of advanced technologies such as recycling options and underground disposal facilities, and by establishing suitable financial, regulatory, and political frameworks.

An integrated view of the **nuclear fuel cycle** is of paramount importance. By identifying and understanding the influences and impacts at all stages of the cycle, effective decisions can be made at the back end of the fuel cycle. This approach guarantees efficient, safe, and secure management of the spent fuel generated.

After interim storage, the spent fuel assemblies must be retrieved and transported to their ultimate disposal facilities for repackaging and disposal. **Nuclear regulatory authorities** in multiple countries seek scientific evidence to support the **licencing process**




High-speed camera video recording sequence during impacting of the MOX specimen (BU = 61 GWd/t)

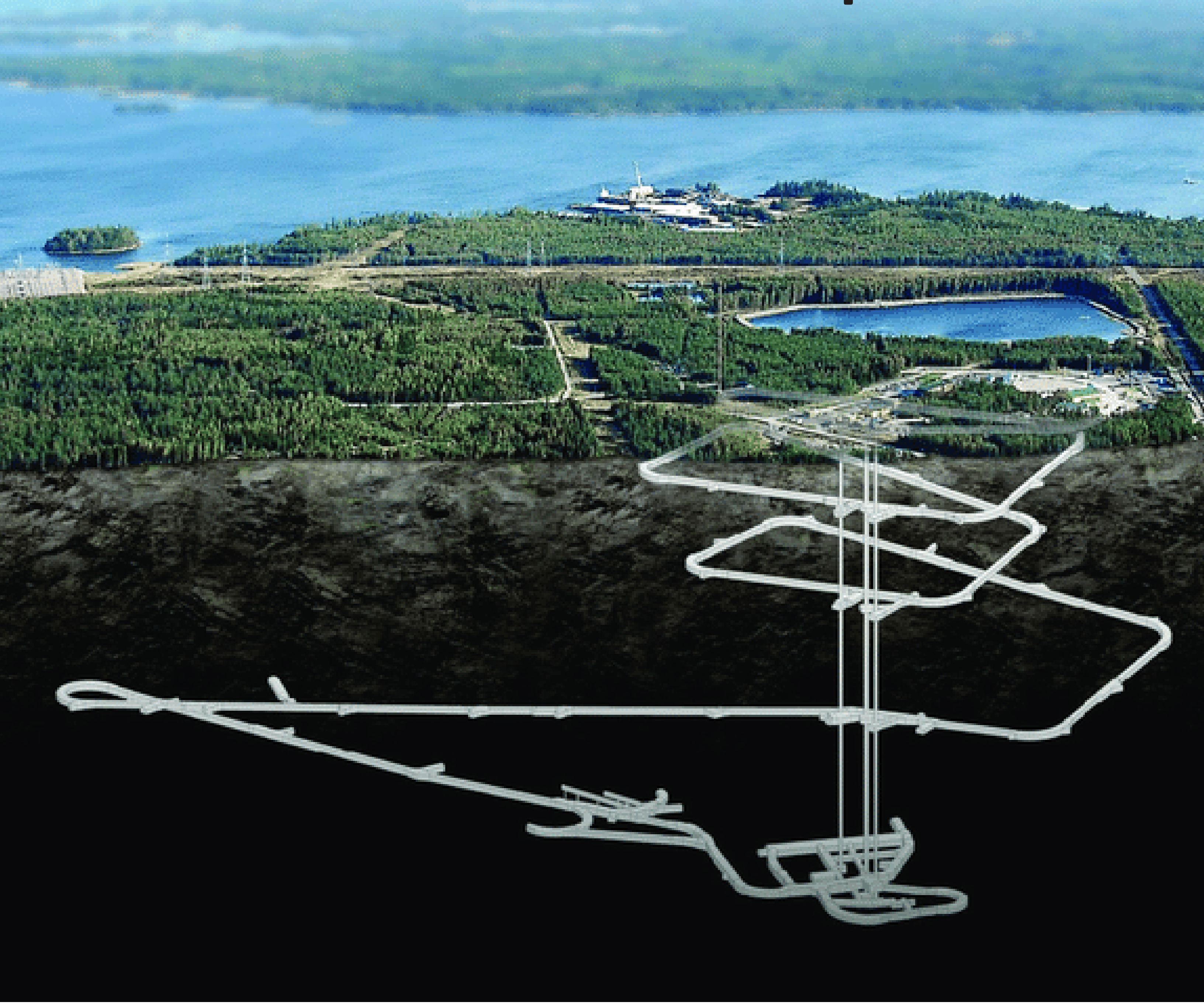
for approving the **extended interim storage of spent fuel**. An essential requirement for the safety of spent nuclear fuel is that the mechanical integrity of the fuel rod be maintained during the handling, storage, and transportation steps associated with spent fuel management. The assessment of specific aspects and processes expected to affect the properties and behaviour of spent fuel during transportation and storage includes direct measurements of spent fuel rods and segments.

JRC's know-how, built on in-house developed devices and experiments, initiated a research area, keeping a leading worldwide role. Unique **home-tailored devices** for gravitational **impact** and 3-point **bending** tests were developed and installed in the JRC hot cell laboratory. The JRC established a basis of **reference data** by performing tests on spent nuclear fuel rod segments to assess the stability of irradiated fuel rods against external mechanical loading, which might be accidentally applied.

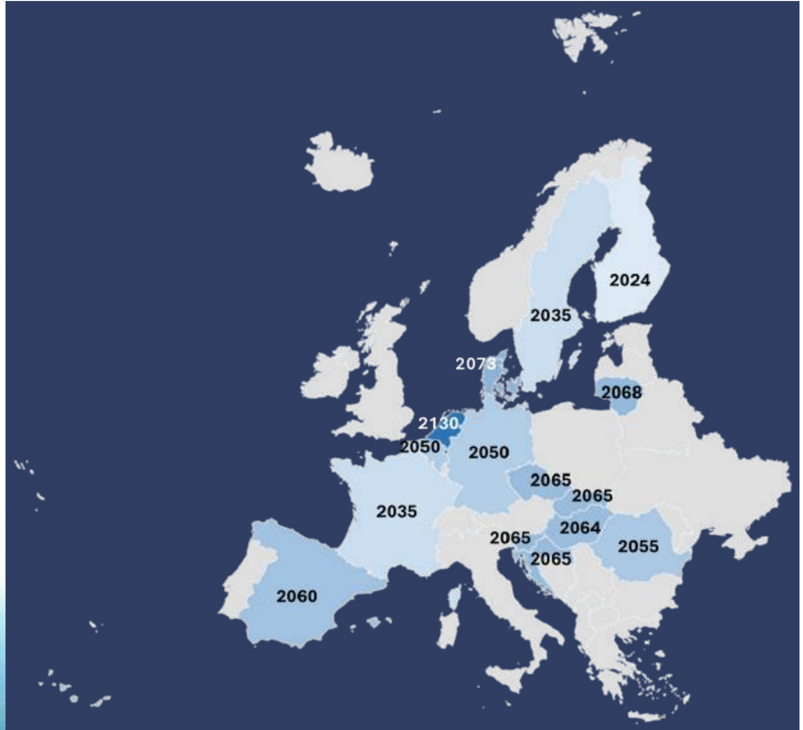
The absorbed energy required for the rupture of the fuel rods during accidental dynamic (impact) or static (bending) loading, the amount and particle sizes of the released fuel, and their dependence on specific cladding and fuel properties, such as burn up, irradiation history, hydride content, and morphology, were determined.

Impact and bending tests on irradiated $UO_2$ and commercial MOX rods over an extended burnup range were carried out. No significant difference in the mechanical stability was observed between the MOX and $UO_2$ SNF rods. The fuel masses released during bending or impact tests are of the same order of magnitude and never exceed the mass of a single fuel pellet. This suggests that fuel dominates the overall SNF behaviour, and the effects of different types of cladding and individual cladding properties per se do not clearly affect the amount of fuel released. At lower burn-ups, owing to the open fuel-cladding gap, increased mass releases were obtained in some individual cases. At higher burn-ups and closed gaps, a general trend of increasing released mass with burn-up was observed. The lower masses of fuel release are expected to be approximately 30 GWd/tHM. Hydride reorientation in irradiated cladding via thermal/pressure treatment is envisaged to study the effect of radial hydrides on cladding stability.

# 04 Radioactive Was Management & Final Disposal



ste




Planned start operation of deep geological facilities in some EU MSs

Council Directive 2011/70/EURATOM on responsible and safe management of spent fuel and radioactive waste defines the need to perform the research, development, and demonstration activities needed to implement solutions for the management of spent fuel and radioactive waste.

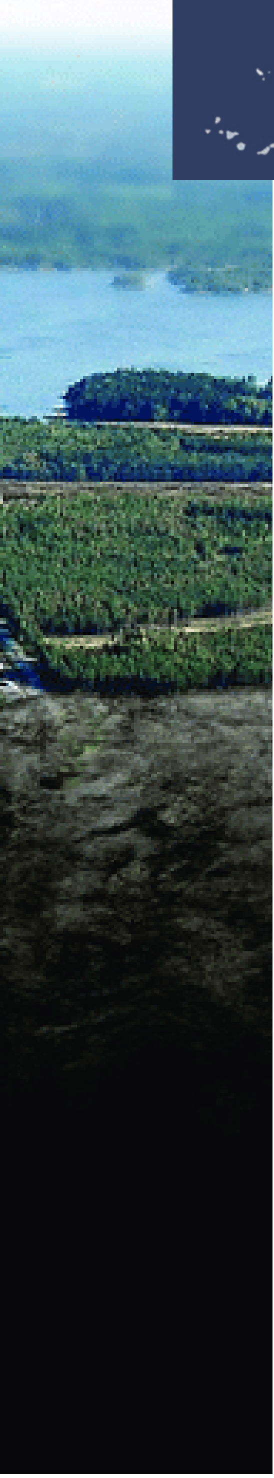
Within the field of responsible and safe management of spent fuel and radioactive waste, the JRC is providing policy support to Member States and Commissions Services, implementing R&D together with Member States, and facilitating international networking. The aim of the scientific-technical investigations is to increase confidence in the safety of disposal solutions. The scientific data and knowledge generated by the JRC feed the modelling of long-term processes and reduce uncertainties in the associated Safety Assessment. The JRC has focused in particular on the **long-term storage and disposal of spent fuel,** supporting the Member State programmes with the output from its unique infrastructure, facilities, analytical instruments, knowledge base, and staff competence. These research activities include not only **conventional fuels** but also **advanded technological fuels (ATF)** and **damaged/molten fuel (corium)** from severe accident scenarios.

JRC activities are embedded in the European Joint Programme on Radioactive Waste Management (EURAD1 & EURAD2), a step change in European cooperation on creating a joint strategic research agenda (SRA) to illustrate the need for research on sustainable management of radioactive waste promoting integrated research cooperation between Member States. The programme is aligned with the strategic vision of Implementing Geological Disposal (IGDTP) and Sustainable Nuclear Energy Technology Platforms (SNETP).

In 2023, the JRC made significant contributions to research in the back-end of the fuel cycle through collaborations with ENRESA and CIEMAT (Spain) to conduct experiments and explore innovative applications of Raman spectrometry in the safety management of SNF.

Incentives to examine both the geological repository and severe accident scenarios were identified together with the IRSN and CEA (France) for short-term collaboration.

The JRC also participates in the TCOFF-2 and FACE projects with the OECD/NEA on post-accident waste management strategies.



The Onkalo disposal facility for spent fuel being constructed in Olkiluoto, Finland (Photo credit: Posiva Oy), is expected to start operation in the middle of the 2020s and will be the first of its kind in the world.

JRC Karlsruhe Hot Cells Laboratory. JRC researchers carry out fuel analysis

# Spent Nuclear Fuel oxidation under dry storage controlled conditions using Raman spectroscopy

This study explored the oxidation of highly irradiated Spent Nuclear Fuel (SNF) under dry storage conditions. Understanding this process is crucial for ensuring the safe management of SNF, as the oxidation of $UO_2$ can lead to the formation of $U_3O_8$, which degrades the mechanical and thermal properties of the fuel and causes its fragmentation.

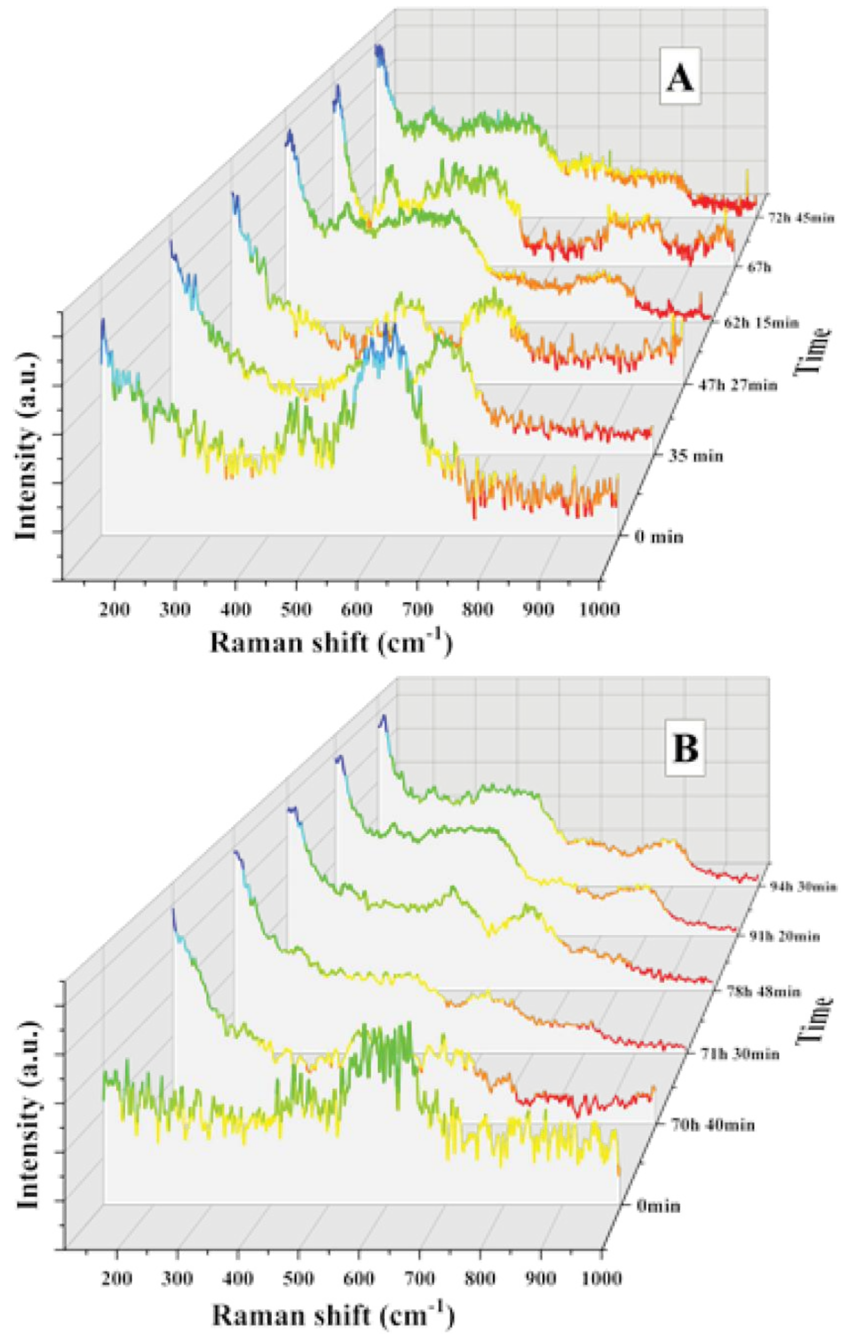
Although previous studies on fuel oxidation have used conventional thermal analysis techniques, Raman spectroscopy is presented as an alternative method that allows the detection of $U_3O_8$ and can follow online changes in $UO_2$ oxidation by identifying the Raman signals of the oxides involved. This work presents a new experimental approach using Raman spectroscopy and a temperature-controlled pressure stage to study the thermal air oxidation of highly irradiated nuclear fuel during storage.

During the experiment, Raman spectra were continuously acquired at different regions of the fuel pellet surface, distinguishing between two main areas: the central part of the sample and a thin region at the periphery of the disk, which was very close to the cladding (not far than 1 mm away from the cladding).

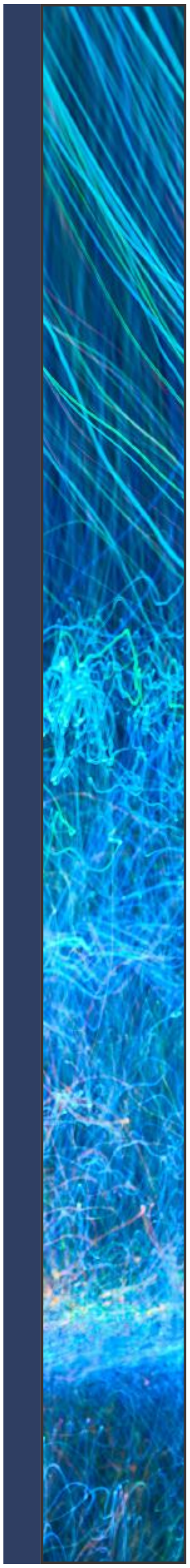
The Raman spectra of the centre (Figure A) show the known transformation of the SNF matrix oxidation from $UO_2$ to $U_4O_9$ and $U_3O_8$ over a temporal frame of approximately 62h, corresponding to the observation of the first $U_3O_8$ spectrum. The oxidation in this region seems to be homogeneous, and the rest of the spectra acquired in this region until the end of the experiment corresponded to $U_3O_8$.

Oxidation close to the cladding (Figure B) follows the same sequence as oxides, but the occurrence of the $U_4O_9$ spectra is much higher, obtaining the first $U_3O_8$ signal after more than 91 h. Unlike the previous case, the heterogeneity of the oxidation is very marked; there are still zones at the pellet rim where oxidation has not been completed, as evidenced by the presence of $U_4O_9$ Raman bands even after 115h.

The results of this work indicate an enhanced oxidation resistance in this area, probably due to the accumulation of fission products and Pu in the area, which stabilises $U_4O_9$ and delays the formation of $U_3O_8$.




Representative Raman spectra acquired during the thermal air oxidation experiment of the irradiated $UO_2$ sample at the A) center and B) close to the cladding. For the sake of clarity, time axis is not scaled.



# Geopolymers: sustainable eco-friendly materials

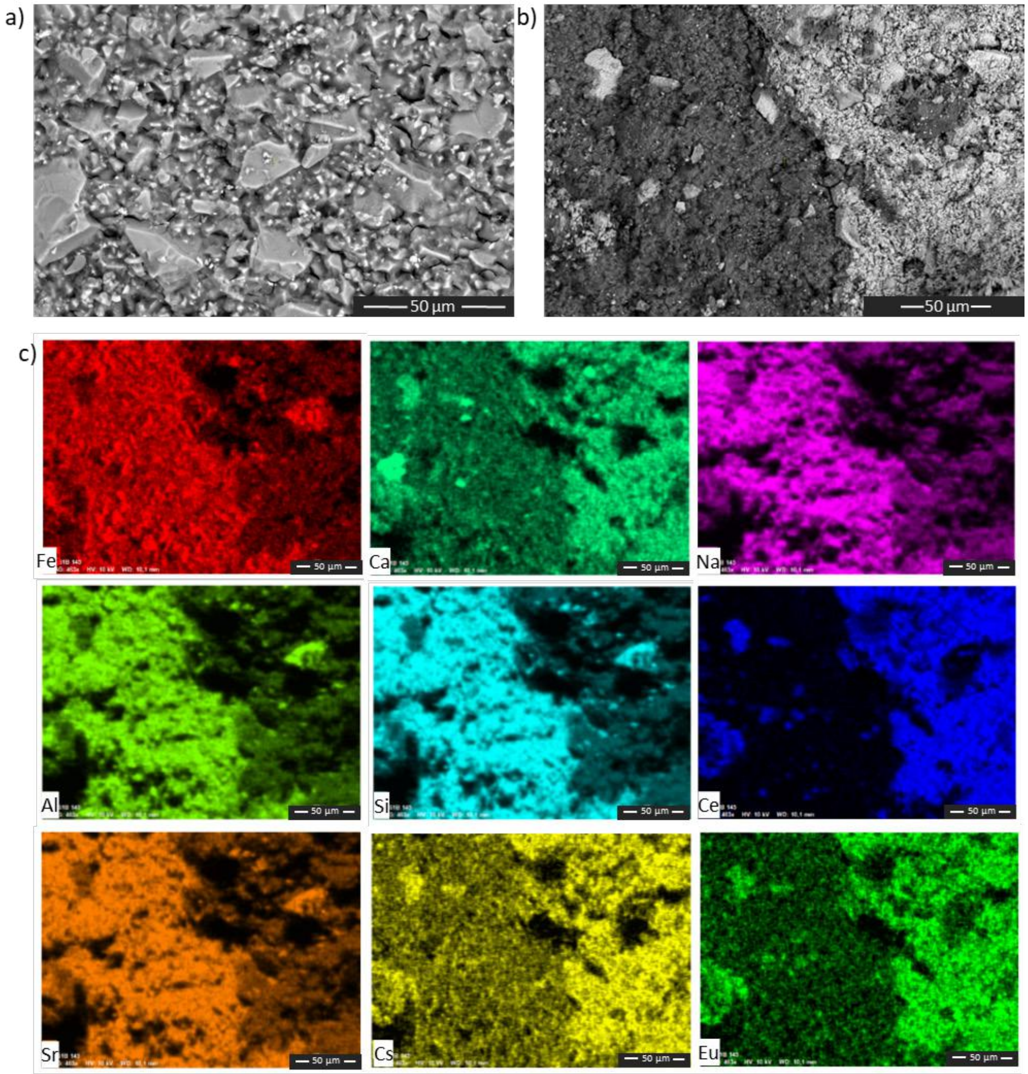
## Immobilisation of radionuclides with nanoparticles and inorganic polymers

The **safe management of radioactive waste** and efficient immobilisation of radionuclides are of paramount importance to prevent their release into the environment and ensure long-term safety. **Liquid radioactive waste** is produced during spent fuel reprocessing, nuclear power plant operations, decontamination measures, and the decommissioning of nuclear installations. Effective and **sustainable** treatment methods are crucial to reduce the potential for radionuclide migration or dispersion during the handling, transportation, storage, and disposal stages.

**Decontamination** involves two major challenges: removing soluble **radionuclides** from contaminated water, and stabilizing/ solidifying them for disposal. Traditional methods involve the first adsorption of radionuclides with ion-exchange resins or other inorganic absorption materials (such as zeolite and bentonite) then concentrating and solidifying it in cement, which results in a high rate of leaching and poor stability over time. **Alkali-activated Materials (AAMs)** have the potential to be more effective than Portland cement in immobilizing radionuclides since they can create stable phases and incorporate them into their structure.

$CeO_2$ **nanoparticles** have gained interest because of their ability to act as free radicals. These nanoparticles, particularly when combined with cellulose acetate, offer mechanical strength and versatility in forms, such as films and membranes. The collaboration between the JRC and the University of Hasselt, Belgium includes a two-step approach: (1) the removal of soluble radioactive contaminants from

SEM of two inorganic polymers a and b, where the lighter areas are CeO2 nanoparticles, and c) EDS-Mapping analysis of sample b. Figures b) and (c) were obtained on the same spot of the sample




wastewater via adsorption on $CeO_2$ nanoparticles and (2) creating a new and effective matrix for their safe immobilization/ encapsulation as a long-term solution. This study concentrates on immobilising radionuclides such as $^{90}Sr$, $^{137}Cs$, and $^{152}Eu$. Dedicated AAMs were synthetised using synthetic Fe-rich slag and doped with different mixtures of $CsNO_3$, $Sr(NO_3)_2$, $Eu(NO_3)_3$, and $CeO_2$ nanoparticles. Samples were analysed during their matrix development using isothermal calorimetry, and studies conducted on their microstructural and physicochemical characteristics. It was observed that increasing the $SiO_2/Na_2O$ ratio delays both the onset and the peak of the polymerisation reaction. This delay is due to the higher $SiO_2/Na_2O$ ratio, which reduces the alkalinity of the solution and slows the dissolution and polymerisation processes. The effects of doping agents were also examined. Specific doping agents significantly delay the polymerisation kinetics of alkali-activated materials, with $Sr^{2+}$ and $Eu^{3}+$ ions having a more pronounced delaying effect than $Cs^{+}$ and $NO_3^{-}$ ions. Stability studies will be conducted to evaluate the capability of the matrix to immobilise radionuclides.

# Geological Repositories

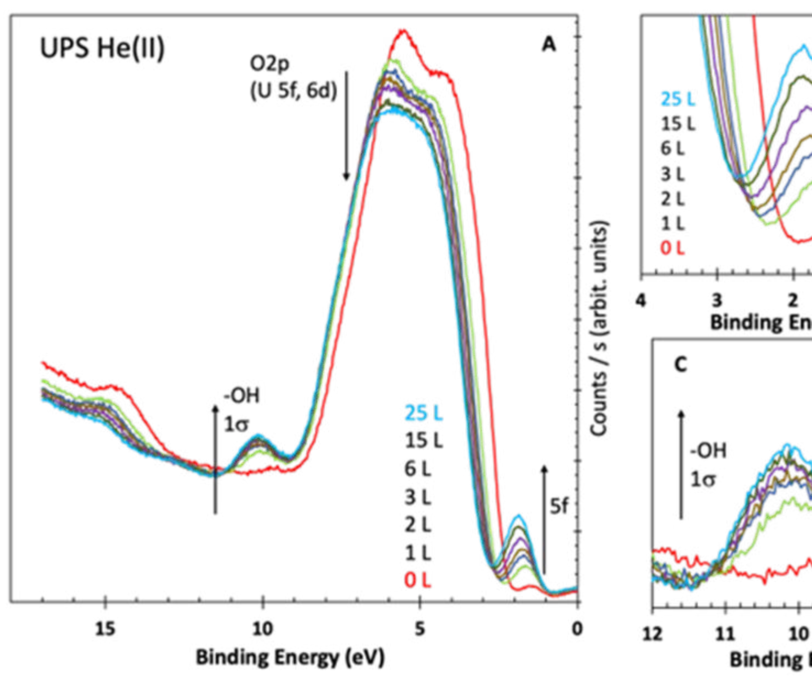
## Monitoring the reduction of $UO_3$ thin film b valence level spectroscopy

Most **geological repository** concepts are based on a mixture of natural and engineered barriers to prevent the intrusion of groundwater into canisters containing nuclear fuel and the migration of radionuclides from the canisters. Although groundwater at many potential repository sites is reduced and $UO_2$ has very low solubility under reducing conditions, the inherent radioactivity of spent fuel can also drive its dissolution.

Oxidation of the surface of $UO_2$ to $UO_3$ or other mixed oxides containing $U^{6+}$ is particularly important because the latter is soluble in water and is therefore of environmental concern for geological repositories in the event of canister failure. Moreover, because of continued radioactivity, molecular and atomic hydrogen atoms are produced by the radiolysis of groundwater and may interact with the surface, potentially leading to the reduction of the oxidised species back to $U^{4+}$ or $U^{5+}$ cations. This counteracted the radiation-driven oxidative dissolution of the $UO_2$ fuel matrix.

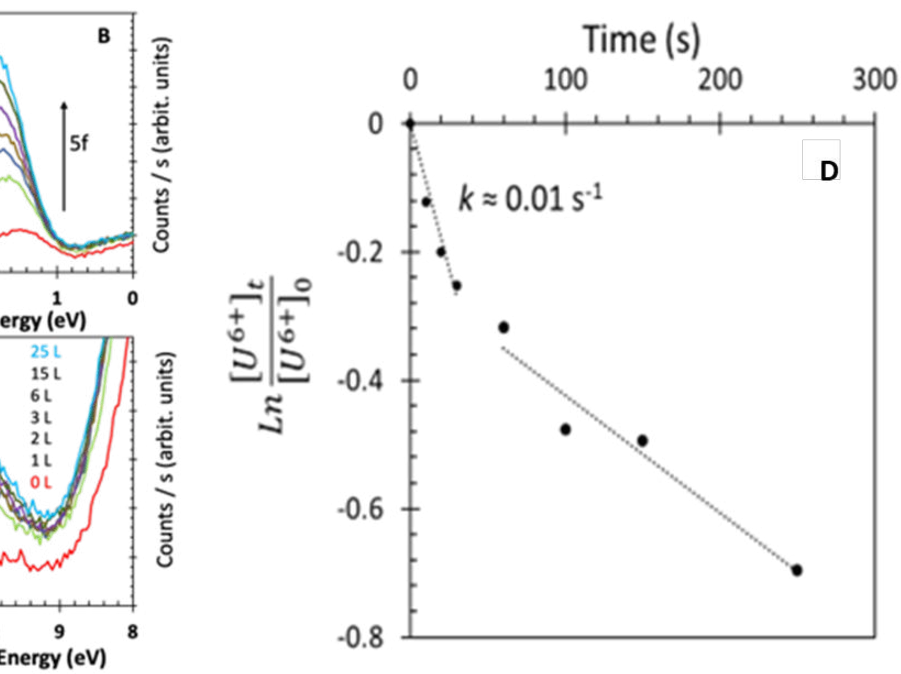
The Surface Science Labstation (SSLS) at JRC Karlsruhe allows for

A: He (II) UPS of UO3 before and after being dosed with atomic hydro ghlight the presence of U5f and surface hydroxyls upon exposure to H upon exposure of UO3 to hydrogen atoms.



# by hydrogen atoms using

gen ($10^{-7}$ Torr) at 190 K. B and C are magnified in the two sections in (A) to hi-
I atoms. D: Change in the concentration of uranium cations with reaction time




the determination of oxidation states in model uranium oxide thin layers by electron spectroscopy under in situ and/or in-operando conditions.

The reaction of a $UO_3$ thin film with atomic hydrogen was studied by He(II) ultraviolet photoelectron spectroscopy (UPS) in the temperature range 190–300 K. The $UO_3$ reduction was instantaneously observed once it contacted H atoms at $10^{-7}$ Torr. The reduction was manifested by the presence of U5f1 electrons in He(II) UPS at approximately 1.5 eV below the Fermi level. Based on the peak characteristics, valence band shape (composed largely of O2p orbitals in addition to some contribution from U6d and U5f orbitals), and X-ray photoelectron spectroscopy (XPS) U4f lines, the reduction of $U^{6+}$ in $UO_3$ only results in the formation of $U^{5+}$ cations and is largely limited to those on the surface.

The reduction was associated with the formation of surface hydroxyls (-OH species) due to the transfer of a proton of the H atom (H.) to the surface oxygen ions, while the electron of H. is transferred to a U5f orbital. The pseudo-first-order rate constant of the initial rate of reduction at $10^{-7}$ Torr and 190 K was approximately 0.01 $s^{-1}$. Qualitative analysis of the valence band before and after reduction indicated that O2p hybridisation with U6d and U5f orbitals leads to well-distinguished features that are characteristic of $UO_3$, $U_2O_5$, and $UO_2$.

# 05

# Radioactivity in the Environment

Bureau International des Poids et Mesures

Radionuclide metrology laboratories at JRc Geel

JRC-Geel operates two highly specialised laboratories, RADMET and the 225 m underground laboratory HADES, at the Euridice site in Mol to perform specialised measurements of decay data, environmental radioactivity, and characterisation of reference materials. Numerous projects aiming at harmonising radioactivity measurements are carried out in the laboratories.

The JRC is represented at the Consultative Committee for Ionising Radiation (CCRI(II)) and consulted for issues linked to the establishment of key comparison reference values and international equivalence. The JRC is also a member of the International Committee for Radionuclide Metrology (ICRM), where the roadmap for future developments is discussed and later decided upon in the European Association of National Metrology Institutes (EURAMET) Technical Committee for ionising radiation.

## Harmonising radioac

Based on Article 8 of the Euratom Treaty, the JRC should promote a common terminology and measurement system for radioactivity. JRC-Geel performs accurate decay data and activity measurements using highly specialised laboratories and instruments. In addition, tools are developed for supporting the International Reference System for radioactivity (SIR), improving international equivalence in the radioactivity field.

Underground laboratory for ultra-low level gamma-ray spectrometry (HADES) at JRC Geel


## Decay Data

Measure and publish new and accurate decay data for radionuclides important for society and science.

## International reference system for radioactivity

Realisation of the unit Bq

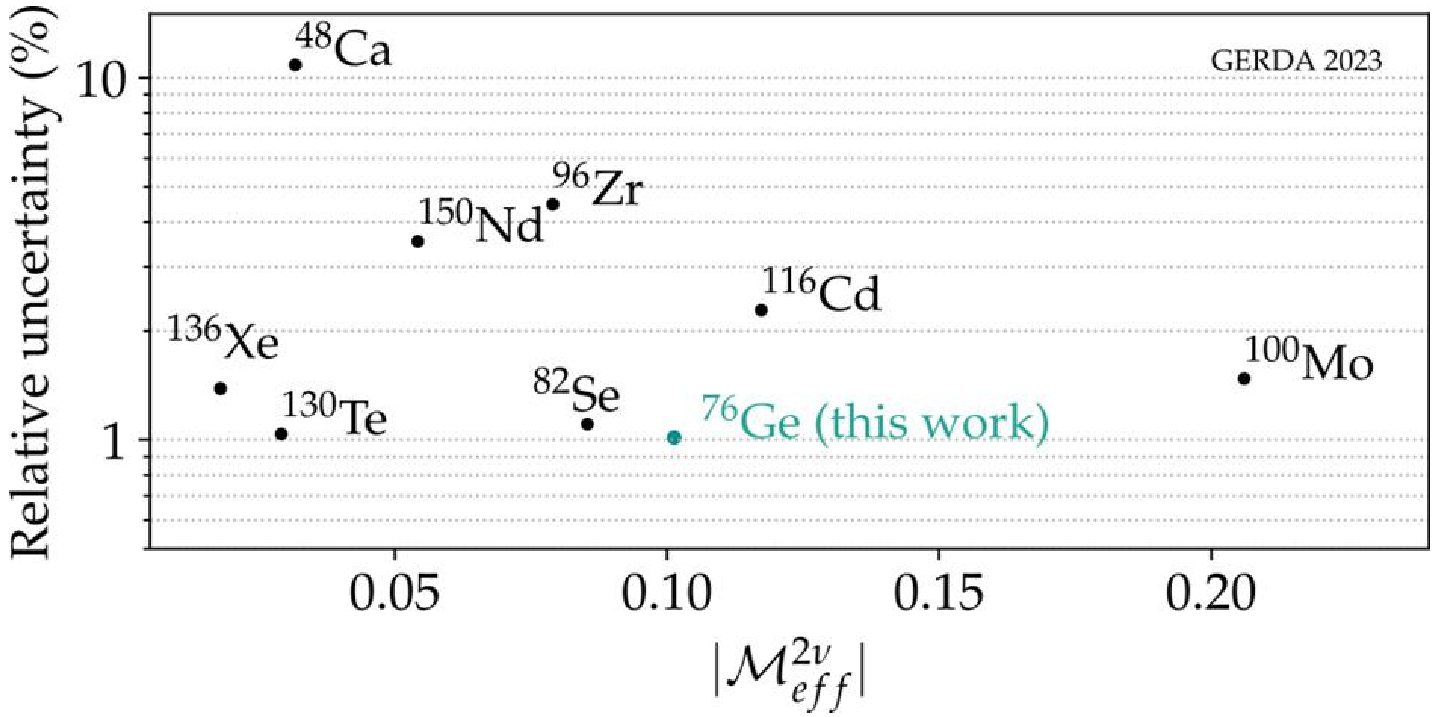
Develop statistical methods for ensuring data treatment and traceability

International harmonisation by contributing to the CCRI(II) work

Participating in key and supplementary comparisons organised by BIPM

# ctivity measurements

## The GERmanium Detector Array (GERDA) – Final results of the Two-Neutrino Double-β Decay Half-Life of $^{76}Ge$




The relative uncertainty of the experimental values of the nuclear matrix element for the two neutrino double-beta decay obtained from different experiments

The international experiment GERDA aimed at building the world's biggest detector for searching for the neutrinoless double beta decay of $^{76}Ge$ using arrays of germanium crystals that were enriched in $^{76}Ge$. A detection of this decay would generate immense understanding for the character of the neutrino including its effective mass and would be a major breakthrough in physics.

The half-life of this rare nuclear process was determined to be $2.022 \times 10^{21}$ years. One of the most important impacts of this number is that one can calculate an experimental value for the so-called nuclear matrix element for two neutrino double beta decay, which is very difficult to calculate theoretically but is essential to convert half-lives to neutrino mass. The low uncertainty obtained from GERDA for this value is shown in the above figure.

The GERDA experiment was located underground at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, in Italy.

Measurements of the activity of beta-decaying radionuclides in reference materials.

A selection of environmental reference materials used for radiological characterisation.

### The most stable half-life measurements ever to be conducted:

The half-lives of $^{22}Na$ and $^{134}Cs$ are important to monitor and used ubiquitously for calibration. In the radionuclide metrology laboratory (RADMET), they have been measured with an exceptional statistical precision under highly stable conditions over 12-14.5 years. The resulting half-lives are more accurate than all the other literature data combined, thus solving a decades-old problem of inconsistency in the literature.

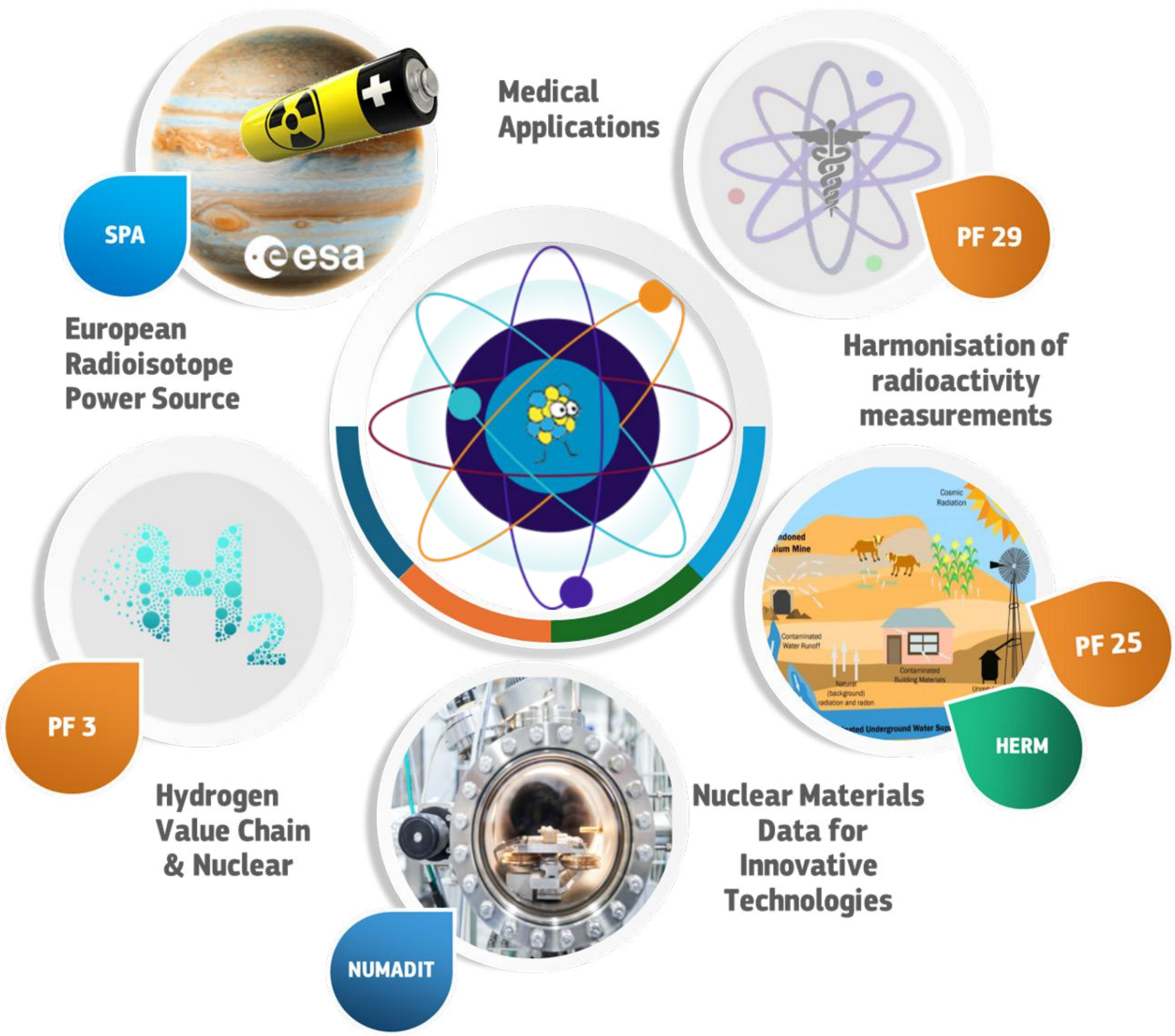
### Support of the fundamental exponential-decay law:

In recent publications, the radionuclide metrology team at JRC-Geel demonstrated how to calculate a complete uncertainty budget for decay data measurements, which is becoming the gold standard for future work in the radionuclide metrology community. The $^{22}Na$ and $^{134}Cs$ residuals to an exponential decay function are exceptionally small and can be fully randomised by compensating for a minor linear dependency on ambient humidity. These datasets provide the most precise confirmation of the validity of the exponential decay law ever recorded. In addition, 140 of the best decay rate measurement series from 14 laboratories worldwide were analysed. It was demonstrated that some datasets are also sensitive to ambient humidity, leading to a distinct annual cycle that can be easily mitigated using historical weather data. As a result, it was proven that all the data series closely adhere to exponential decay. This evidence contradicts the speculation that radioactivity is influenced by varying the solar neutrino flux impacting Earth. Owing to the JRC's work in this area, the international community is reassured that the exponential decay law is still a valid cornerstone of the common measurement system for activity.

### Support to the international measurement system for radioactivity:

The JRC provided a theoretical formula that successfully predicts the observed time-interval distribution in a digital nuclear spectrometer. This implies that also the precision of every-day nuclear measurements is under statistical control. JRC contributed to the IAEA comprehensive report on the safety review of the ALPS-treated water (Advanced Liquid Processing System) at the Fukushima Daiichi Nuclear Power Station. The JRC developed an Empirical Mode Decomposition method to evaluate uncertainty aspects in time series and demonstrated its use in half-life measurements performed at the PSI, Switzerland.

# 06 Nuclear Science Applications



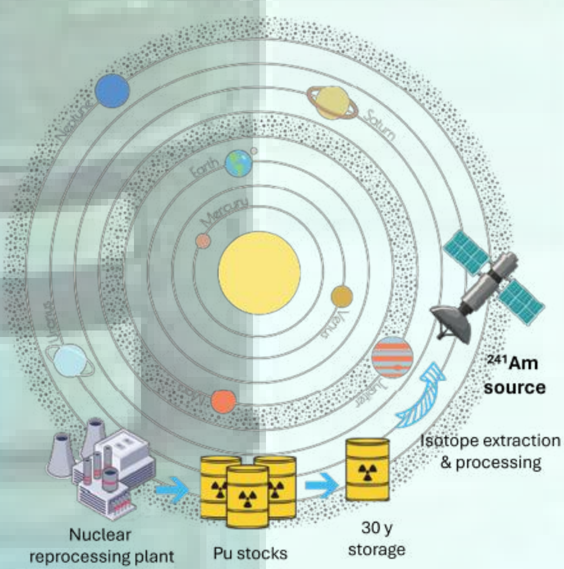

Nuclear science applications in the PF4, main projects and portfolio synergies.

# Space Applications

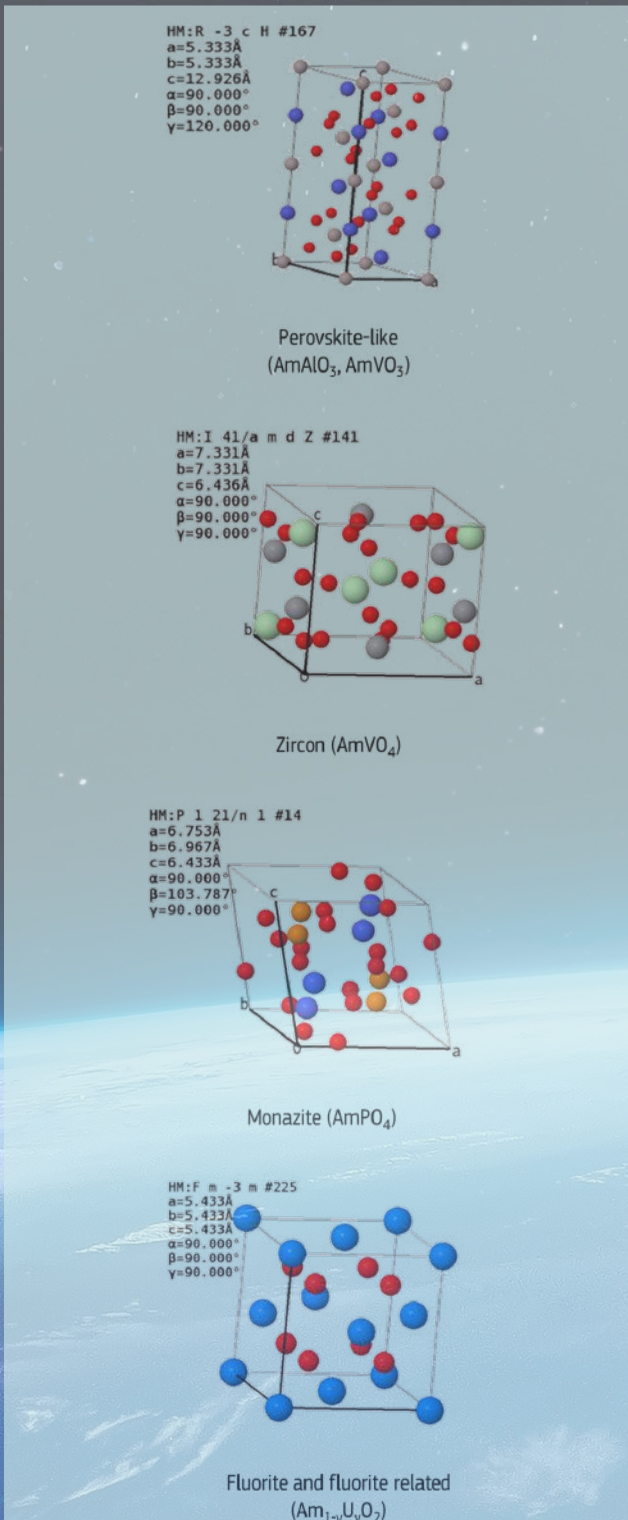
EU space policy focuses on the promotion of scientific and industrial competitiveness and addresses the impacts of the EU's space investment on the EU's political priorities, such as the European Green Deal, the Digital Decade, and strategic autonomy.

The JRC has become a significant contributor to the creation of a **European space power source** utilizing $^{241}$Am

Radioisotope Power Systems are **Key Enabling Technology** for Space Exploration




The Euratom Research and Training Programme for 2021-2025 has increased the emphasis on **non-power applications of nuclear technology.** In this domain, the **medical field** is the most prominent, with Euratom supporting **Europe's Beating Cancer** Plan. There is also much potential for nuclear science in fields such as agriculture, environment, and space. The JRC works in close cooperation with EU Member States, international organisations, and industry, and operates unique nuclear infrastructure. The efficient use of these facilities, combined with the expertise of the core research staff in the JRC, enables a wide array of activities, from medical to space applications. The development of **Radioisotope Power Systems (RPS)** is a key enabling technology for the exploration of deep space, where the sun cannot deliver sufficient power to spacecraft. The JRC established itself as a key player in the development of a European space power source based on $^{241}$Am, an alternative to $^{238}$Pu. The JRC and the ESA concluded a collaborative research arrangement, making the JRC an important partner for nuclear power sources and materials for the **ESA** and the JRC is also participating in the Euratom PULSAR project on the buildup of a European production capacity and radioisotope power source based on $^{238}$Pu. The JRC investigates specific nuclear materials relevant to the hydrogen value chain of green transformation (**Hydrogen Value Chain & Nuclear**). Some **noble metals** that can act as catalysts are present in **spent nuclear fuel**. The project focuses on the potential use of hexagonal close-packed (HCP or epsilon) particles as catalysts for liquid organic hydrogen carriers (LOHC) used for hydrogen storage and transport.




Americium ceramic compounds produced at the Minor Actinide Laboratory of JRC Karlsruhe

The Treaty of Lisbon (2010/C 83/01) created a legal basis for European Space Policy. Article 189 of the Treaty on the Functioning of the EU defines the main objectives of space policy to promote scientific and technical progress and industrial competitiveness. The exploration of space requires a reliable supply of heat and electricity. Solar panels provide the energy required for missions inside an inner solar system. However, when the space probe travels into the shadow of planetary bodies to the outer regions of the solar system (or beyond), the solar intensity is no longer sufficient, and nuclear power sources are currently the only feasible option.

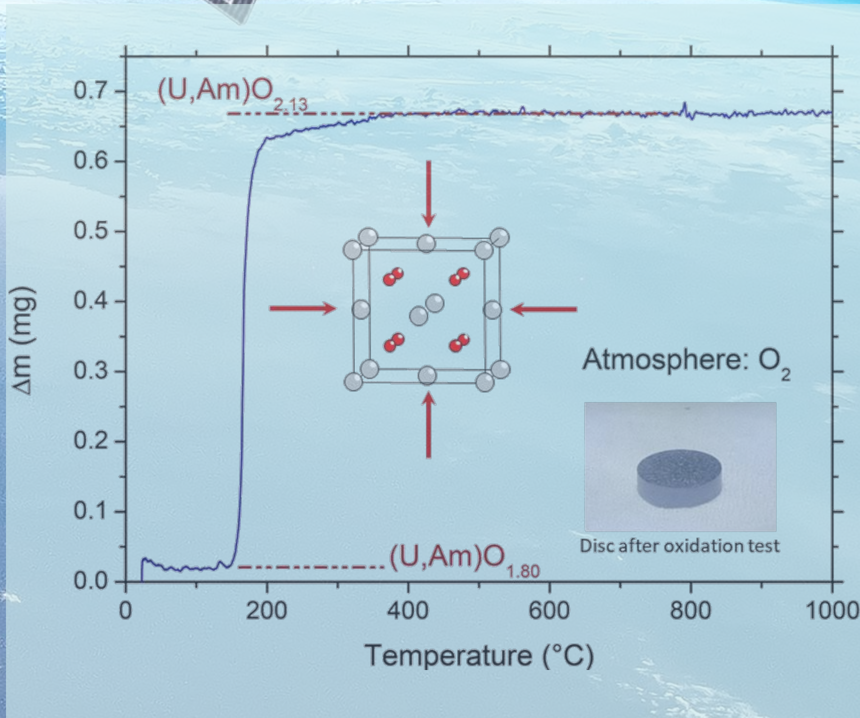
The European Space Agency has decided to develop a Radioisotope Heating Unit (RHU) and a Radioisotope Power Source (RPS) for future exploration missions based on the decay heat of the radioactive isotope $^{241}$Am. This isotope belongs to the so-called minor actinides and is available in large amounts in European plutonium stocks after reprocessing as a decay product of $^{241}$Pu. This isotope is highly radiotoxic and emits significant gamma radiation. The requirements for a stable form are diverse, ranging from stable and safe behaviour during storage on earth and operation in space to good performance in the case of various accident and post-accident scenarios.

The JRC established itself as a key player in the development of a European space power source based on $^{241}$Am, an alternative to $^{238}$Pu. The JRC prepares innovative Am compounds, investigates their safety-related physical properties, and assesses the safety of heat sources using analytical and experimental methods.

The Minor Actinide Laboratory of JRC Karlsruhe represents a unique facility for the preparation and characterisation of highly radioactive minor actinide-containing samples and to explore the safe preparation of such nuclear heat sources.

“The JRC contributes significantly to the future Am-241 based radioisotope power systems for an independent European space research program”

Stabilisation method developed for $AmO_2$ using U as a dopant

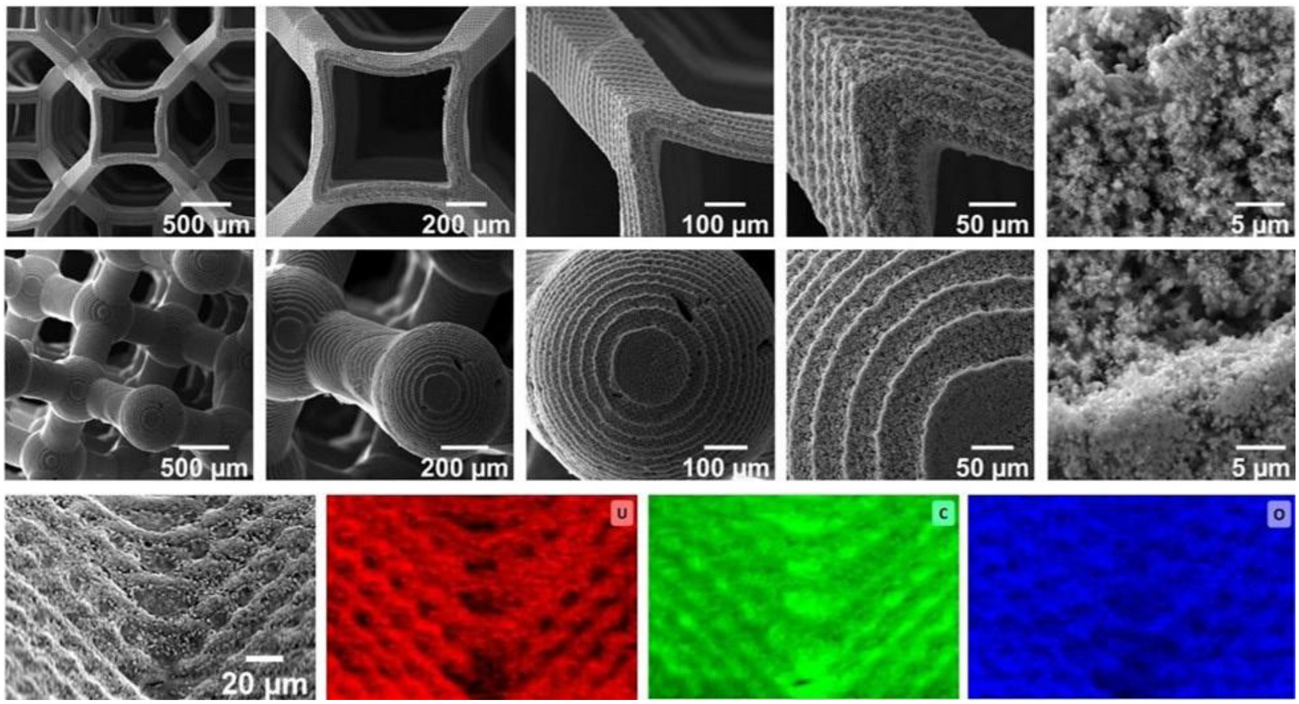



Ceramic compounds $Am1\text{-}vUvO_2$, $AmPO_4$, $AmAlO_3$, $AmVO_3$, and $AmVO_4$ were produced. The structural and thermo-physical properties at high temperatures were assessed using existing equipment such as XRD, laser flash, drop calorimetry, and laser melting. Owing to intense alpha activity, self-damage occurs rapidly. The defects were characterised by XRD, RAMAN spectrometry, NMR, SEM and TEM.

A stabilisation method was developed for $AmO_2$ using U as a dopant, and the safety-relevant properties, thermodynamic stability, and compatibility with the envisaged cladding materials were assessed.

A welding methodology for high refractory cladding materials was developed, and prototype safety capsules were manufactured. Two types of Pt30Rh-encapsulations were constructed at JRC Karlsruhe, and welding tests were performed. Non-destructive and destructive weld examinations were performed, which showed that good welding results were achieved, indicating that future welding quality criteria can be met.

Chemical and morphological characterization of the printed components. SEM images of representative complex parts upon carbothermal reduction. SEM and EDX mapping images of the uranium carbide/carbon nanocomposite sintered at 1700°C for 24 hours



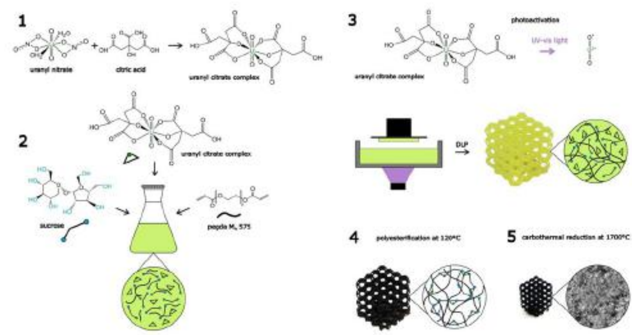

# First Additive Manufacturing of 3D Uranium-Based structures for nuclear applications

Over the past few decades, growing interest in rapid prototyping has driven the widespread adoption of **Additive Manufacturing (AM)** technologies across cutting-edge sectors in modern industries. These sectors include the aerospace, automotive, energy production, and medical applications. AM enables innovative designs and previously unattainable geometric complexity, thus offering a valuable methodology for creating high-performance components. These components are typically fabricated to withstand extreme operating conditions.

These complex-shaped AM components exhibit multi-material layouts and cellular structures, combining functional attributes such as extreme temperature resistance, ultralight weight, and high reliability. Among these diverse applications, AM has recently garnered significant attention in the nuclear field. Researchers have explored AM technologies to produce internal reactor components in nuclear power plants. Although still primarily conceptual, the substantial design freedom provided by

AM has paved the way for innovative nuclear-fuel architectures. One intriguing aspect of AM is its ability to intentionally engineer the


Optical images of the as-printed components and upon sintering



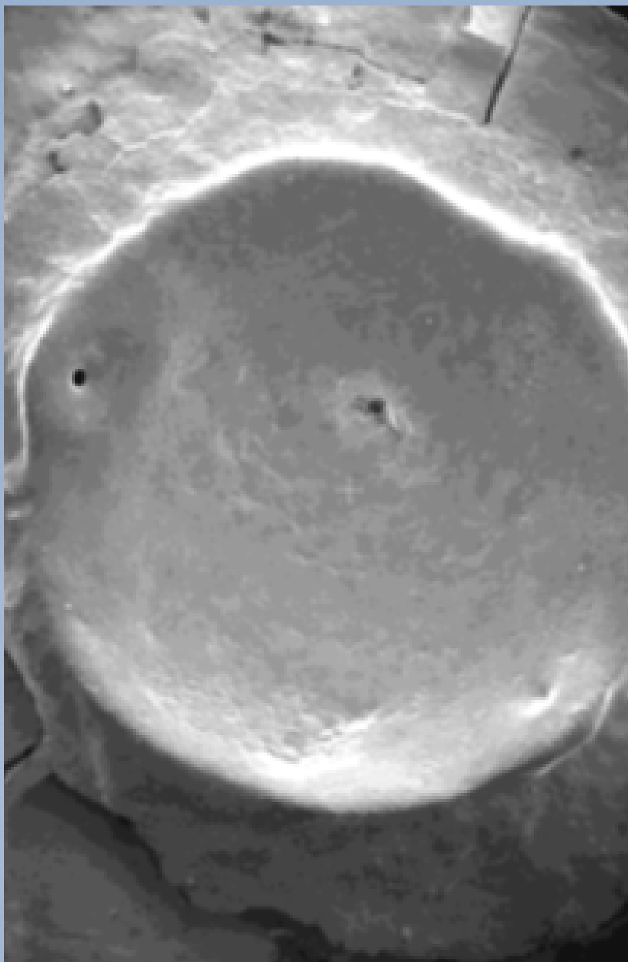
Schematic protocol for the fabrication of uranyl-containing complex component

porosity of printed components. This deliberate porosity can lead to substantial improvements in both the thermomechanical performance and the physical functionality of actinide systems used in **nuclear fuel applications**. Furthermore, the ability of AM to create three-dimensional periodic structures has revolutionised the fabrication of **complex-shaped** parts. Components such as reticulated structures exhibit outstanding mechanical strength, lightweight design, and improved thermal conductivity. Their large surface area and inherent porosity make them ideal for extreme heat-resistance applications.

Uranium significantly impacts global politics and energy economy. This offers groundbreaking opportunities for energy production in nuclear power plants. Uranium-derived materials, particularly novel uranium-based compounds, show promise owing to their high densities and thermal properties. These materials include **uranium mononitride**, **uranium silicide** ($U_3Si_2$), and **uranium carbides**. In particular, uranium carbides are essential for producing various radioactive species used in nuclear medicine. Additionally, the uranyl cation ($UO_2^{2+}$) exhibits unique photochemical properties, making it a potential photocatalyst for water-based sol-gel inks. This approach overcomes the limitations related to photoinitiators and enables photopolymerization without their use.

JRC investigated an **innovative synthesis protocol** to explore the use of uranyl cations as photocatalyst systems for photocurable sol-gel-based formulations by coupling the **photochemical reactions** of uranyl cations with photopolymerization-based additive manufacturing processes.

A versatile methodology was developed for the preparation of a sol-gel formulation to fabricate complexshaped uranium carbide/carbon nanocomposites via Digital Light Processing (DLP). The chemical pathway involves the UV-visible light photoactivation of uranyl ions, which was **exploited for the first time** for the photocleavage of alkene bonds, thereby triggering photopolymerization reactions and fabricating complex geometries. The inherent flexibility of this sol-gel approach allows the extension of its utility to other uranium-based compositions, such as oxides, charting a path forward for the development of new applications for 3D printable micro-architected uranium complexes as valuable catalysts and novel advances in the fields of molecular biology, nuclear medicine, and physics.



Scanning Electron Microscopy image of the molten area of $Ta_2C_{1.5}N_{0.5}$

Advanced materials (AMs) are one of the Key Enabling Technologies defined by the European Commission and are strategic value chain identified by DG GROW. AMs are an important factor for the **competitiveness** of European industries and are crucial building blocks for the **EU's resilience and open strategic autonomy.** The demand for advanced materials is expected to increase significantly in the coming years and should be matched by increased innovation and production in the EU.

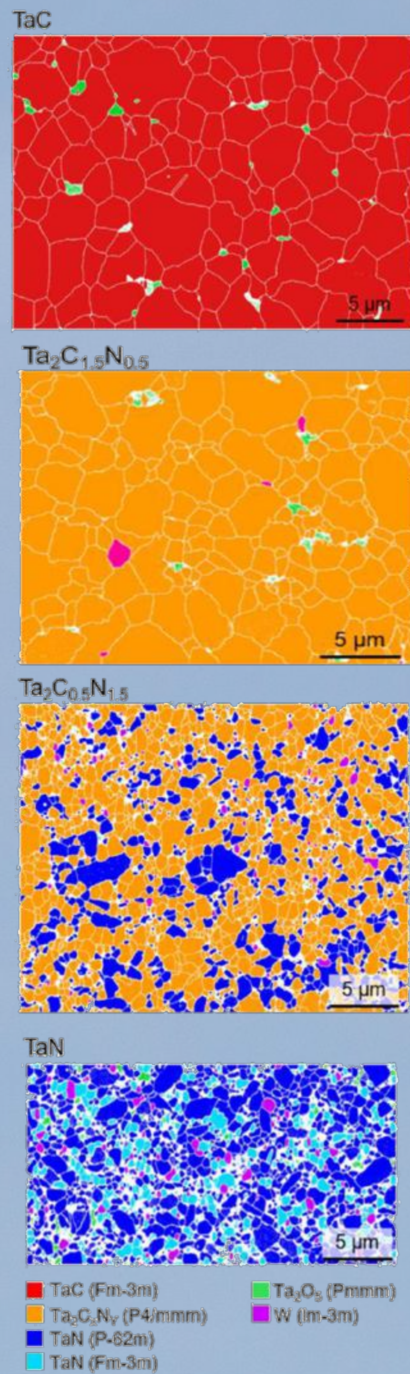
AMs encompass all new materials and modifications of existing materials to obtain superior performance in one or more characteristics that are critical for applications in energy, mobility, construction, and electronics, as they are particularly important for achieving the **twin transition**. In this context, high-performance refractory materials play an important role in applications ranging from gas turbines and heat shields for hypersonic vehicles and space shuttles to irradiation targets and advanced nuclear fuel concepts. Such materials are also called "ultra-refractory", as they can maintain their structural stability at temperatures exceeding 3000 K. In particular, carbides of some transition metals (Ta, Hf, Ti, and Zr) and their solid solutions have

"**ultra high temperature ceramics** hold world record highest melting point"

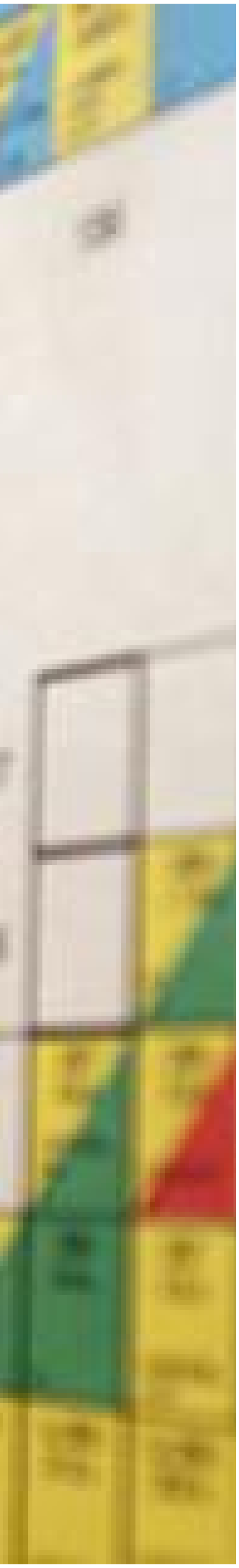
been shown to display the highest melting point and structural stability. Tantalum carbide (TaC) and hafnium carbide (HfC) are of particular interest because of their high melting temperatures (> 3500 K) which have been the highest reported values for nearly a century.

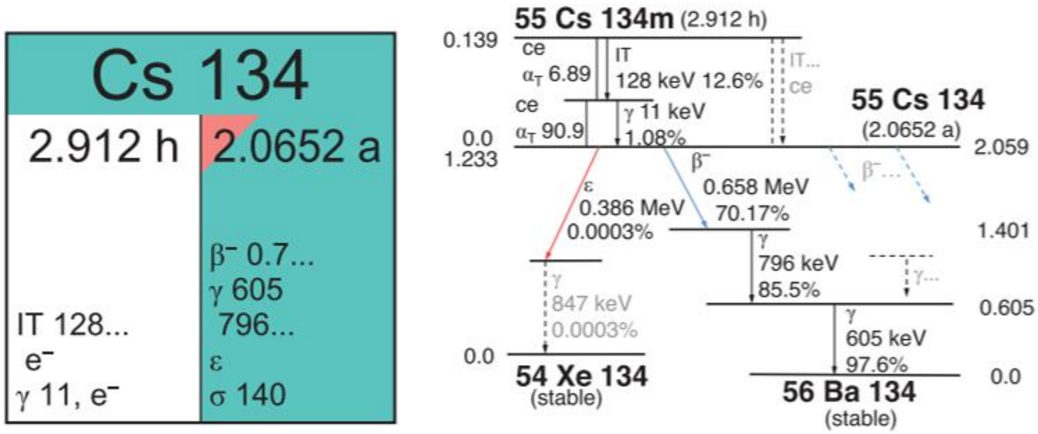
However, the synthesis and characterisation of **ultra-high temperature ceramics (UHTC)** is a very challenging area of materials science and engineering because of the scarcity of characterisation techniques at such extreme temperatures and challenges in their synthesis in bulk forms. Indeed, the powders are highly oxygen sensitive, and their refractory nature makes the production of a dense product extremely difficult using conventional methods.

The JRC performed a comprehensive study of such novel materials in the Hf-Ta-C-N system from their synthesis to their mechanical properties and chemical and very-high-temperature characterisation. JRC demonstrated that it is possible to sinter and obtain dense pellets by Spark Plasma Sintering at a temperature (1873 K) at least 200 K lower than that usually reported for this type of material. Furthermore, the Young's moduli of the synthesised compounds, as determined by nanoindentation, were higher than those reported for TaC or other UHTCs, demonstrating the good quality and high density of the samples obtained with the sintering process.




Spatial distribution of phases in the synthetized samples by Electron Backscattered Diffraction.






Nuclide box and the reduced decay scheme for 134Cs and 134mCs

The study of isotope properties, synthesis, and decay modes is instrumental for rationalising phenomena, providing a basis for our understanding of the universe, and resulted in a plethora of applications with deep societal and economic impacts.

Understanding isotopes contributes to powering spacecraft, elaborating sophisticated climate change models, deploying accurate environmental control systems, and applying powerful diagnostic and therapeutic tools for fighting diseases.

The **Karlsruhe Nuclide Chart** (KNC), which celebrates its 65th anniversary in 2023, provides scientists and students with nuclear data on 4122 experimentally observed ground states and isomers, the most recent values of the atomic weights, isotopic abundances, and cross sections.

It contains structured, accurate information on the half-lives and decay modes of radionuclides, as well as the energies of the emitted radiation. Beyond the more traditional physical sciences such as health physics and radiation protection, nuclear and radiochemistry, and astrophysics, the chart is now widely used in life and earth sciences. It also has great didactic value for **education and training in nuclear sciences**.

Scientists at Karlsruhe, Germany, commenced this project 65 years ago by launching the inaugural edition of the Karlsruhe Nuclide Chart. Since 2005, the European Commission's Joint Research Centre in Karlsruhe has provided support and updates for the chart. During this time, we have released five new editions, with the most recent, the 11th edition, published in 2022. This new version includes fresh and updated radioactive decay and thermal neutron cross-section data on 1035 nuclides, 82 of which were not present in the previous 2018 edition.

JRC Karlsruhe is updating and supporting the Karlsruhe Nuclide Chart

# Open Access Nuclear data

# HORIZONTAL ACTIVITIES 07

# HORIZONTAL ACTIVITIES 07

*“It”s a nice working environment with a lot of technical equipment and experienced workers“*

Open Access to JRC Research Infrastructures

Use the JRC Labs for Research

According to the Euratom Treaty, the **JRC’s central bureau for nuclear measurements** in Geel has a strong mandate to act as a European reference for promoting a standard system of measurements in nuclear physics and nuclear chemistry.

Nuclear applications with large societal impacts, such as fission and fusion nuclear energy, medicine, and security, require **reliable nuclear data** for the validation of physical models on which engineering developments and licencing requirements are based. The required nuclear data are provided in the evaluated libraries, which are compilations of the recommended nuclear data used as a reference. The experimental work at JRC-Geel is guided by the needs to improve these libraries.Moreover, the JRC produces and characterises a variety of targets for high-precision measurements of neutron reaction data at the GELINA and MONNET accelerators.

The JRC provides evaluated data and recommendations for the Joint Evaluated Fission and Fusion (JEFF) project, and accurate decay data are integrated into the evaluated libraries of the Decay Data Evaluation Project (DDEP) and the Evaluated Nuclear Structure Data File (ENSDF). The JRC contributes to the decay characteristics of radionuclides relevant to detector calibration, nuclear medicine, environmental monitoring, nuclear safety, security, safeguards, and waste management.

**European research infrastructure for nuclear reaction, radioactivity, radiation and technology studies in science and applications (EUFRAT, Geel)**

- Neutron time-of-flight facility for high resolution neutron measurements (GELINA)
- Underground Laboratory for ultra-low-level gamma-ray spectrometry (HADES)
- Tandem accelerator based fast neutron source (MONNET)
- Radionuclide metrology laboratories (RADMET)

**Actinide User Laboratory (ActUsLab, Karlsruhe)**

- Properties of actinide materials under extreme conditions (PAMEC)
- Fuels and material research (FMR)
- Hot cell laboratory (HC-KA)

**Laboratory for environmental & mechanical materials assessment (EMMA, Petten)**

- Assessment of nuclear power plants core internals (AMALIA)
- Liquid Lead Laboratory (LILLA)
- Micro-Characterisation Laboratory (MCL)
- Structural materials performance assessment laboratories (SMPA)

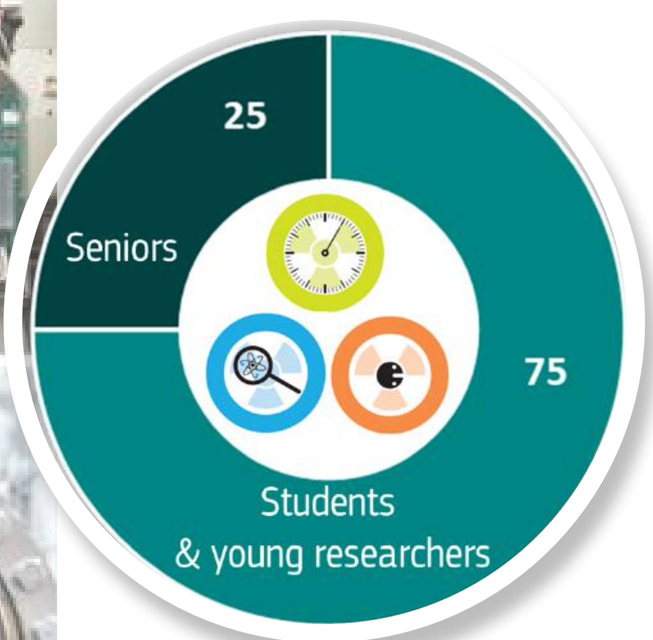
The **nuclear research infrastructure** plays a key role in delivering and stimulating high-quality research and innovation. They require a specific technological laboratory configuration with highly trained personnel, licence, and access to strategic materials. **Open access to JRC research infrastructure** opens the doors of the Commission to the European community of researchers, who can benefit from European expertise and infrastructure. Since 2017, the JRC has decided to open 17 of its high-value research facilities to external users in an open-access scheme, including nuclear laboratories.

In this context, access to the JRC nuclear facilities is free of charge for Member States and countries associated with the Euratom research and training program. Enabling a successful synergy of direct and indirect actions, in 2020, the JRC and DG Research and Innovation signed a financial arrangement to provide financial support to external users for their travel and subsistence. The project aims to promote training and mobility between academic institutions, research centres, and industry and the JRC, and to maintain multidisciplinary nuclear competences at the highest levels in the EU.

The open access scheme relies on the use of nuclear infrastructure located in Karlsruhe, Geel, and Petten. Three calls have been issued since 2020 and the JRC has accepted 83 proposals. About 70% of the proposals include the participation of students and young researchers, post-docs, PhD, or master's students, which highlights the importance of the open access scheme in transferring knowledge and preparing the next generation of nuclear scientists and engineers.

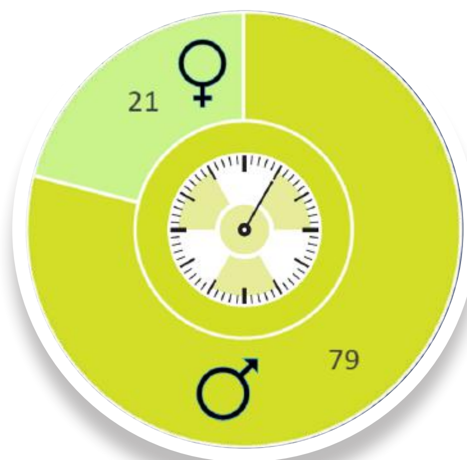
Making JRC research infrastructures accessible Europe-wide enables better cross-border cooperation to build a stronger European Research Area, bridging highly- and lesser-developed European regions, and contributes to building and maintaining scientific and technical competences all around Europe. Therefore, it promotes European cooperation and innovation and contributes significantly to the training of younger generations of researchers and technicians, which is becoming a critical issue in the nuclear field.

# Open Access in numbers




USERS PROFILE % (2017-2023)

Over the period 2020 – 2022 around **42 %** of the total users were **students** when they were accessing to the research infrastructure (RI).

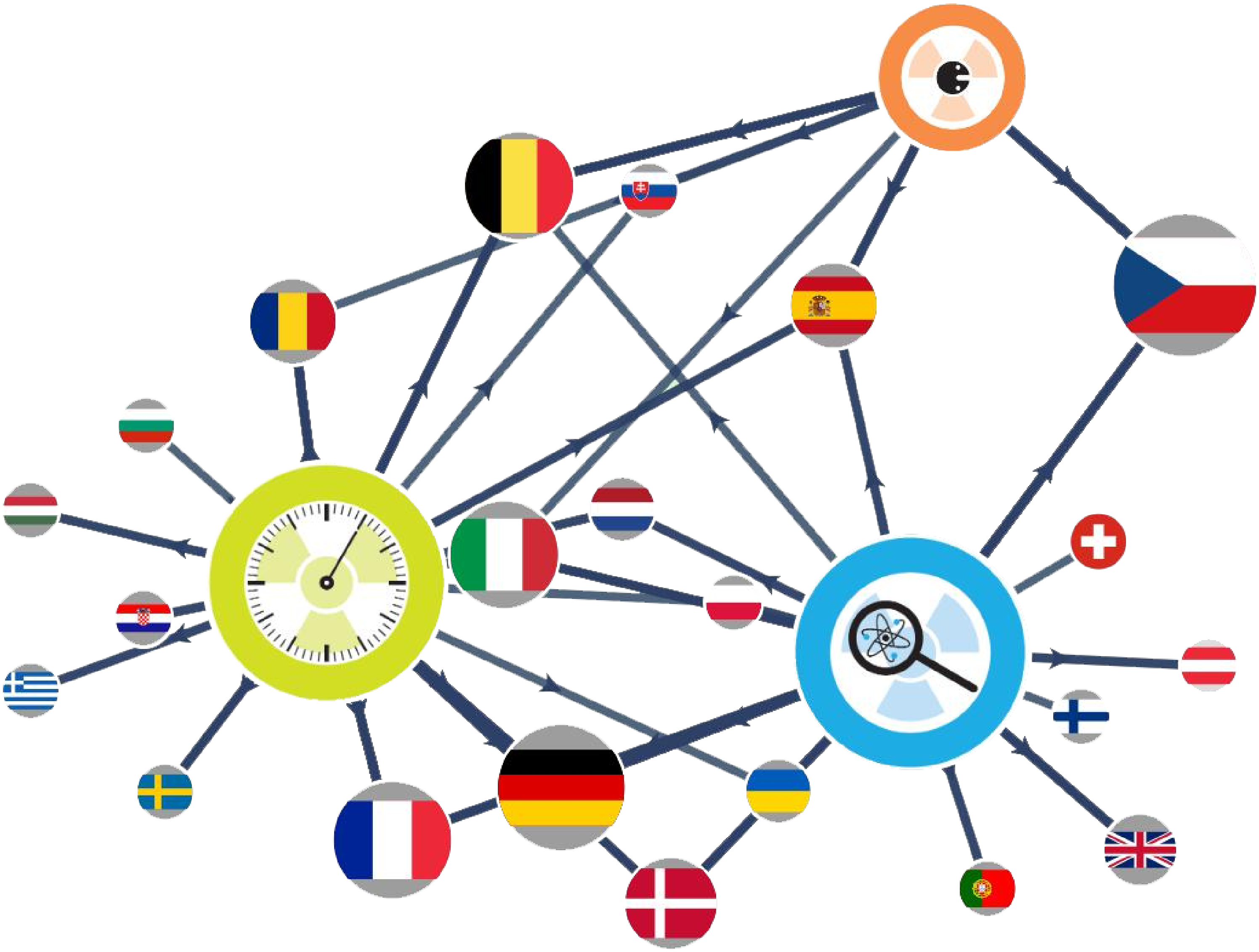



EUFRAT

Gender representation of JRC open access users (%, 2020-22)

PUBLICATIONS

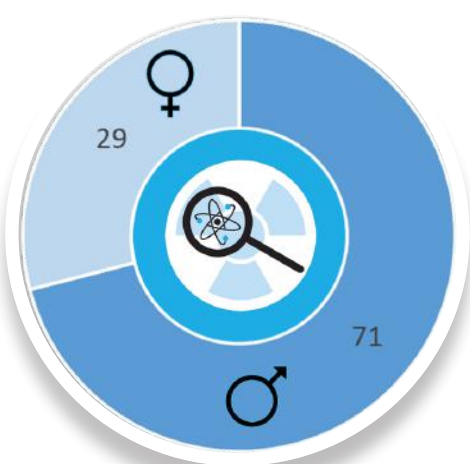
Articles published in peer reviewed journals. **More than 50 publications** with JRC co-authors.



## Nuclear RI Open Access Users Network (2017-2023)

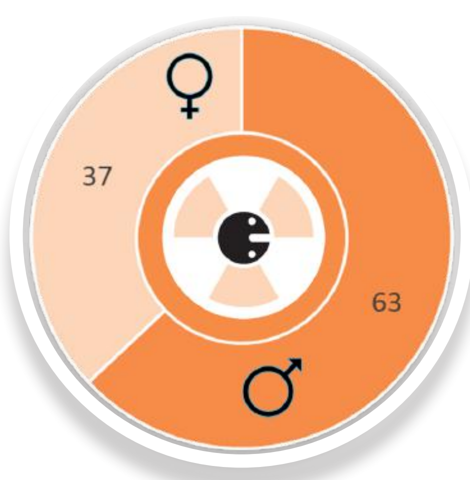
Flag size indicate number of projects implemented.

A total of **382 scientists** from **35 countries**.




ACTUSLAB

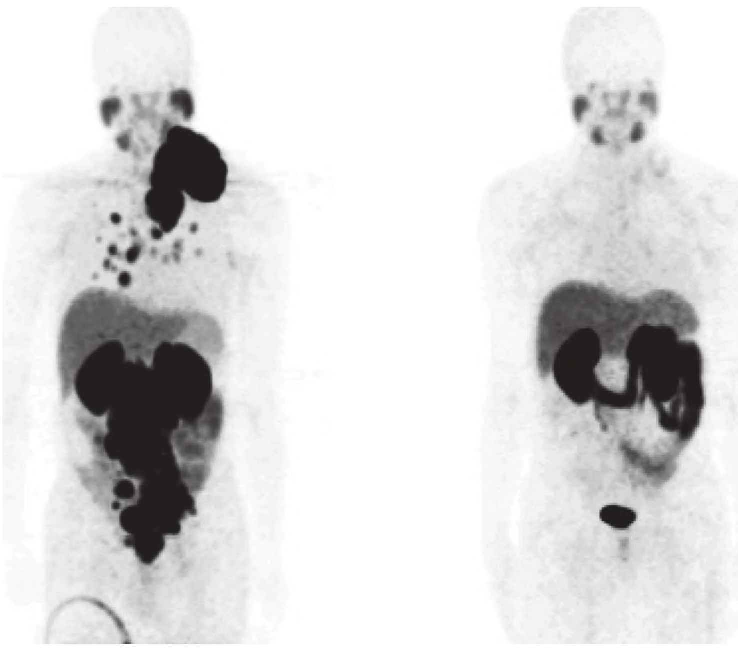
Gender representation of JRC open access users (%, 2020-22)

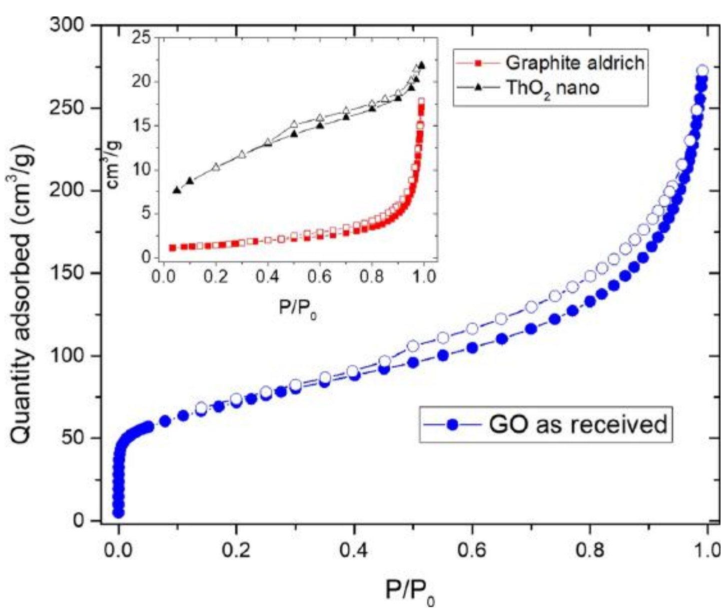



EMMA

Gender representation of JRC open access users (%, 2020-22)

Response to therapy after two cycles of $^{225}$Ac-PSMA-617 demonstrated by $^{68}$Ga-PSMA-11 PET/CT images of a patient with metastatic castration-resistant prostate cancer.






Isotherms collected for original GO and graphite. GO displays a remarkably high SSA, which is advantageous for actinium production.

Targeted Alpha Therapy (TAT) is considered an extremely promising approach to treat cancer. This treatment selectively destroys tumour cells wherever they are in the body, including at the metastatic stage, when surgery or radiotherapy is no longer possible.

Among the potentially employable alpha-emitting radioisotopes for this purpose, $^{225}$Ac has recently attracted much interest because of its combination of a suitable 10-day half-life, the emission of four alpha particles in its decay chain, and the generation of $^{213}$Bi, another isotope considered for TAT applications.

The development of $^{225}$Ac-based radiopharmaceuticals presents several challenges, mostly linked to the availability of sources and/or production techniques for this isotope and the purity of the obtained products.

A team from the Istituto Nazionale di Fisica Nucleare (INFN, Italy) and the University of Padova (Italy) studied **innovative target materials** to produce $^{225}$Ac in the JRC Karlsruhe **PAMEC and FMR laboratories**.

Thorium carbide (ThC2) nanoparticle targets prepared from different starting materials (graphite and graphene oxide) were tested and compared. The results clearly indicate that the ThC2 targets using graphene (ThC2–GO) exhibit much better properties for the ISOL (Isotope Separation On Line) method, a technique used for the production of radioactive ion beams, and could therefore be used as highly efficient targets for producing $^{225}$Ac.

The results of this study have been published in Scientific Reports, a high-quality journal. The lead user and main author of the publication are young researchers and among the other users and co-authors, one was a PhD student at the time of the proposal.

## Isolation of ultra-high purity $^{239}Pu(III)$ oxalate

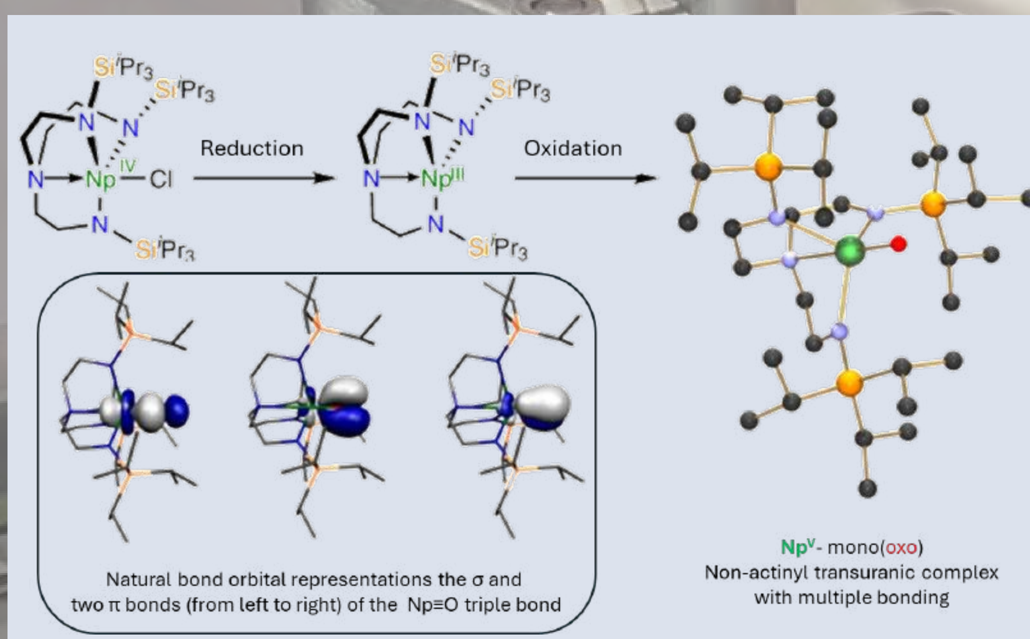
A international team led by theuniversity of Florence (Italy) has successfully synthesised, isolated, and characterised a stable molecular neptunium (V)-mono(oxo) triamidoamine complex using the **ActUsLab Research Infrastructure PAMEC** in collaboration with JRC scientists.

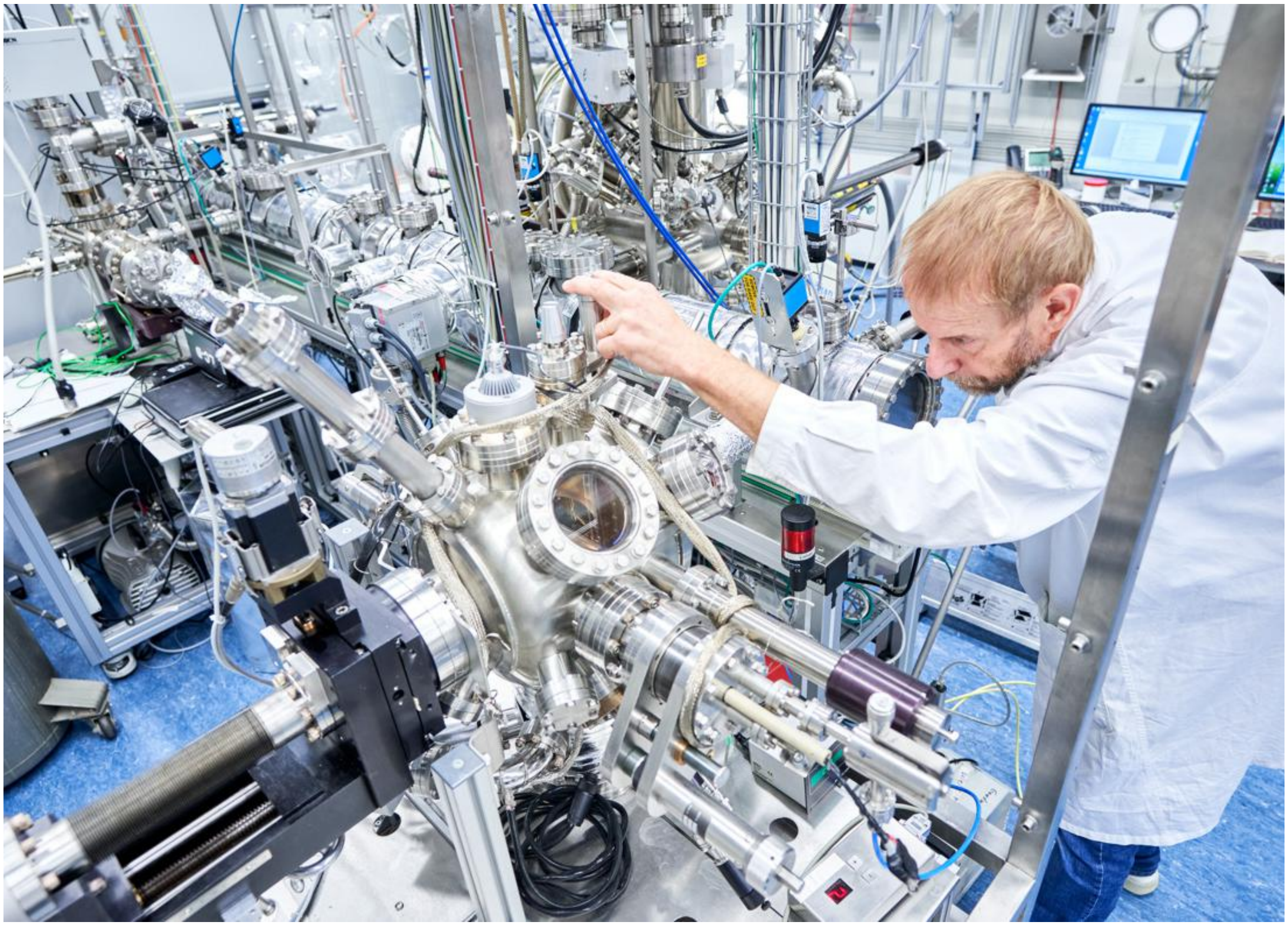
This work has demonstrated that molecular high-oxidation-state transuranic complexes with a single metal-ligand bond can be stabilised and studied in isolation.

This paves the way for future studies on **transuranic-ligand multiple bond complexes**, with the long-term goal of better understanding and predicting **heavy element electronic structures**.

The development of theory and improvement of models with predictive capabilities regarding the basic properties of **actinide** elements and compounds are crucial for optimising the safe use of these materials in power and non-power applications. The results of this study were published in [Nature Chemistry](). The main user and first author of this high-impact publication was a former PhD student at JRC Karlsruhe. At the time of the proposal, he was a post-doc and has now obtained a permanent position to work in the nuclear field.

## Synthesis, isolation, and characterisation of a stable molecular neptunium(V)–mono(oxo) triamidoamine complex.





Scientific equipment for photoemission, atomic force microscopy, and electron scattering measurements at the PAMEC laboratory.

Research reactors comprise a wide range of different reactor types that are not used for power generation. The primary purpose of research reactors is to provide a neutron source for research, including education and training, and various applications, such as material testing and the production of radioisotopes for medicine and industry.

Since the mid-1990s, fuel research and development in civilian research reactors has focused on developing fuels to reduce uranium enrichment. Uranium-molybdenum (U-Mo) alloys are the most promising fuel type for the conversion to low-enriched uranium (**LEU**) fuel. Information on the material properties of all **LEU U–Mo fuel** constituents is essential for fuel designers and reactor operators to evaluate the performance and safety of these new fuels.

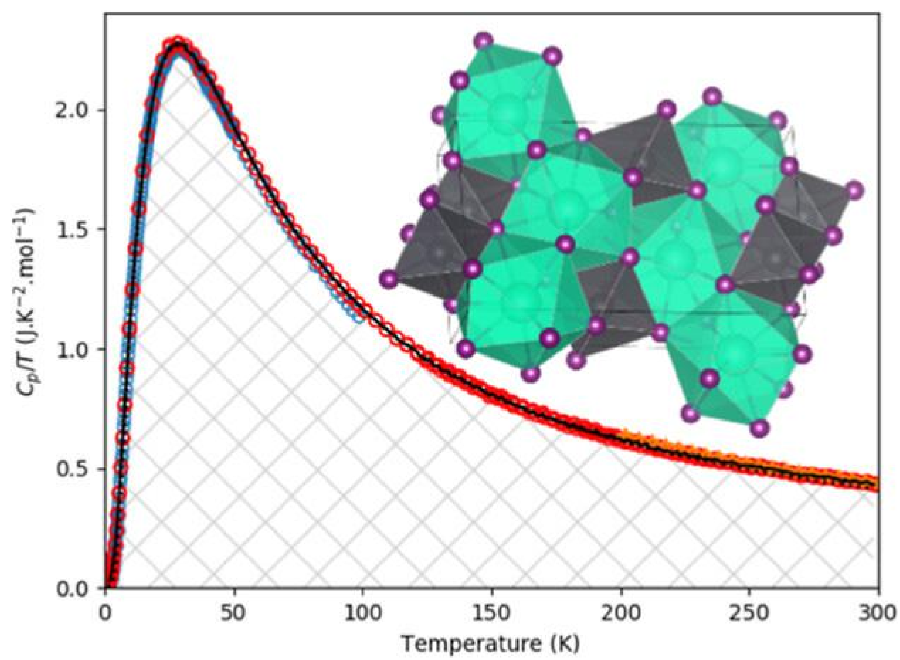
The production of uranium-based films is advantageous over bulk material studies because it allows the performance of advanced physics and chemistry experiments on small amounts of radioactive material. Nanometre-thick thin films can be routinely fabricated using various methods, for instance, sputtering. By stacking such thin films in multilayers, layered systems with properties that are completely distinct from those of constitutive bulk materials can be created.

A Czech team from Charles University and the Institute of Physics, Czech Academy of Sciences (Prague, CZ), in collaboration with JRC scientists from the ActUsLab Research Infrastructure PAMEC, successfully studied the crystal structure and magnetic and electrical properties of thin U–Mo films and their hydrides prepared by reactive sputter deposition from metallic targets.

This research allows the study of fundamental aspects of nanoscale physical phenomena, with a focus on the giant magnetoresistance effect (GMR) observed in multilayers composed of alternating ferromagnetic and non-magnetic conductive layers based on uranium.

The **Lead-cooled Fast Reactor (LFR)** was selected as one of the six key designs for next-generation nuclear reactors by the Generation IV International Forum. The coolant in LFRs is either lead (Pb) or lead-bismuth eutectic (LBE). Numerous **fission products** (FPs) are generated during irradiation; important classes are volatile fission products (Cs, I, Te) and semi-volatile elements (Ba, Sr), which have the most serious consequences during a nuclear accident. In particular, the formation of Cs(g) at the periphery of the fuel is of concern, as a possible release of $^{135}$Cs and $^{137}$Cs into the coolant could occur in the case of a clad breach.

A team from the Delft University of Technology (NL), in collaboration with JRC scientists from the ActUsLab Research Infrastructure PAMEC, investigated the interaction chemistry between the irradiated fuel and coolant, and the assessment of the driving force for the release of volatile FPs into the coolant after a clad breach. For a comprehensive thermodynamic assessment of the **Pb–Bi–Cs–I** system, **thermodynamic and phase diagram information** is necessary. The low-temperature heat capacity up to room temperature was measured, providing insight into the physics and thermodynamics (heat capacity and entropy) of complex metal iodides. The Physical Property Measurement System (PPMS) of the **PAMEC facilities** was used for the low-temperature heat capacity measurements.




Experimentally measured heat capacity of $CsPbI_3$. $CsI–PbI_2$ system (perovskite-related phase).


View of the part of PAMEC facilities, including the Physical Property Measurement System (PPMS)

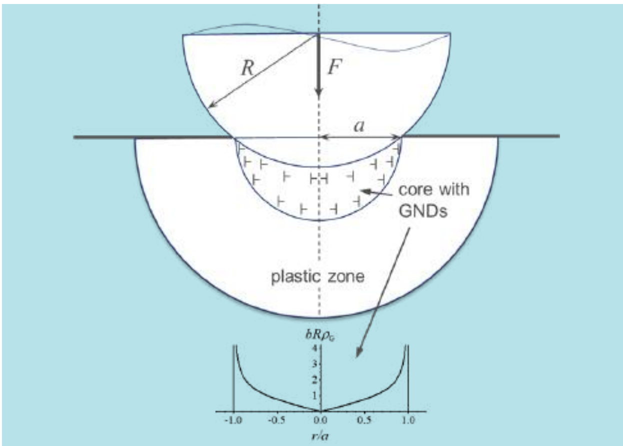
The JRC Petten Micro-Characterization Laboratory (MCL) contributes to the development of material performance assessment methodologies based on micrometer-sized specimens.

Reliable **mechanical testing** techniques are required to assess the safety of structural materials in nuclear environments. The miniaturisation of tests and micromechanical test methods play an important role in accelerating the mechanical performance assessment, reducing the amount of material needed for testing, and limiting the activity of the irradiated material.

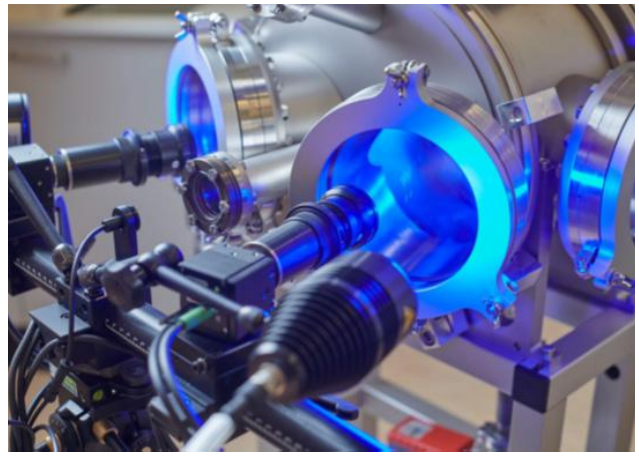
The **MCL laboratory** focuses on experimental studies of microstructure and micromechanics, providing insights into the complex coupling between the microstructure, its defects, and the mechanical behaviour of small volumes of metals, ceramics, polymers, and composites.

New best practices for small specimen testing and the conduction of micromechanical tests have been developed and validated in the fields of nanoindentation, membrane bulge testing, and micropillar compression, along with new physics-based schemes for data reduction and reliable derivation of mechanical material performance data. The results were validated and compared with the conventional mechanical properties derived from standard tests. The work was supported and further promoted by advanced data management to facilitate the reuse of data for material qualification and performance modelling.

During 2023, four EMMA Open Access projects were conducted in the MCL and LILLA laboratories in cooperation with scientists from three different member states.




Model adopted to obtain stress–strain curves from spherical nanoindentation.



Set-up allowing MBT at elevated temperatures with non-contact temperature control using a thermal imaging camera.

**Nanoindentation** is a technique that uses a spherical tip to measure the flow stress of materials under plastic deformation. While it theoretically allows for the creation of an indentation stress-strain curve, practical challenges, such as variable constraints, size effects, and the relationship between plastic strain and indentation depth, introduce uncertainties.

To address these issues, a **new mathematical model** was developed. This model integrates an expanding cavity model for the plastic zone with a hemispherical core model that accounts for geometrically necessary dislocations. This combination helps to consider both the constraint and size effects accurately.

The model framework combines an expanding cavity model for the plastic zone with a 1D model for the hemispherical core containing a distribution of geometrically necessary dislocations (GNDs) that shape the advancing indent (Figure left).

A **new protocol** based on this mathematical framework was established to derive the stress-strain curves. This protocol was validated against standard tensile test results, proving to be a significant enhancement in the accuracy and capability of the nanoindentation method for assessing material performance.

**A miniaturised membrane bulge test was adapted for nuclear applications:**

The membrane bulge test (MBT) is used in the automotive industry for sheet metal forming investigations. It is readily combined with non-contact deformation measurements by 3D digital image correlation (DIC) to allow a direct and precise derivation of stress–strain curves during membrane stretching, thereby avoiding the limitations of other test techniques for which bending is not negligible.

A **miniaturised MBT** for the use of thin metallic foils with a thickness of a few tens of micrometers was proven and successfully implemented. This is of particular interest for nuclear applications when it comes to limiting the activity induced by **neutron irradiation**. The shallow thickness of the membrane also provides an advantage in the case of charged particle irradiation, featuring a limited penetration depth.

Research has been performed on various sets of metals provided in sheets with thicknesses between 10 µm and 300 µm.

The test results show high reproducibility and the capability of the technique to obtain true stress–true strain curves, yield stresses, Young's moduli, and rupture stresses and strains.

The setup also allows performing tests at elevated temperatures with non-contact temperature control by pyrometry and thermal imaging (figure right).

**WAE Project: Measurement of the $^{17}O(n,p)^{17}N$ cross section in the neutron energy range 10-20 MeV using the water activation (ENEA, IT)**

Water is commonly used in the nuclear industry as a heat-transport medium. It is used as coolant in many fission reactors, but it is also proposed to cool the reactors of fusion devices such as ITER. Neutrons can react with oxygen of water molecules, leading to activation of the water circulating in the facilities. Water activated by fast neutrons emits both high-energy gamma rays and neutrons, which require proper shielding and pose a radiation hazard to personnel and instrumentation. The $^{17}O(n,p)^{17}N$ reaction produces the isotope $^{17}N$, which has a half-life of approximately 4 s and decays, emitting beta, gamma, and neutron radiation. The reaction cross-section is affected by large uncertainties, and only a few experimental data points are available in the EXFOR database. This database, also known as the EXFOR library (IAEA), contains an extensive compilation of experimental nuclear reaction data from more than 22000 experiments.

The WAE experiment used the MONNET accelerator to produce monochromatic neutrons with variable energies to activate demineralised water in a circulation system. Experimental analysis is still in progress. The aim of the experiment is to provide new data for the cross-section in a wide neutron energy range, from below 10 MeV to above 16 MeV. This will improve the accuracy of water activation calculations and support the **safety limits for nuclear plants and future fusion technologies.**

MONNET is a high intensity quasi mono-energetic neutron source driven by a vertical 3.5 MV Tandem accelerator producing either continuous or pulsed ion beams.

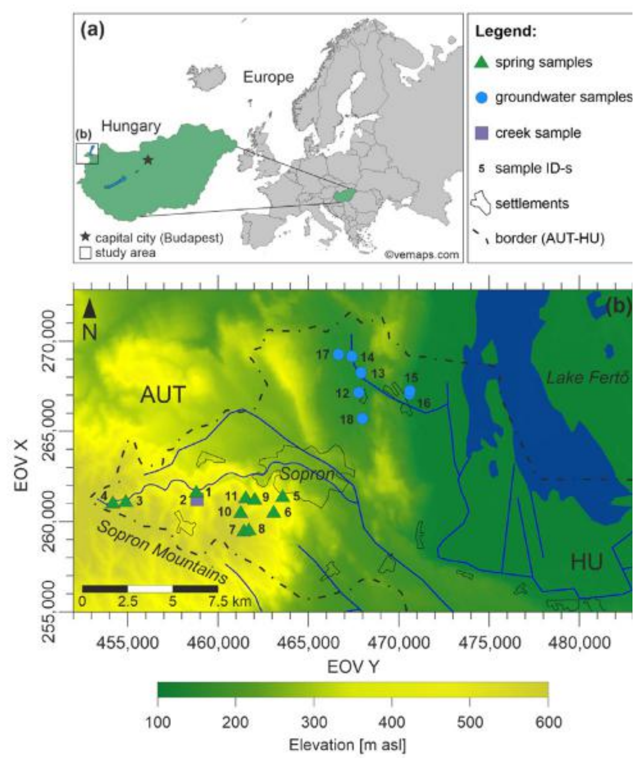
The Radionuclide Metrology Laboratories (RADMET) are a cluster of instruments for both radiological characterisation of materials and high accuracy radioactivity measurements.

A team of Hungarian scientists collaborated with the JRC in the UnderGRad project (Understanding Groundwater Radioactivity) to assess measurements of natural radioactivity in groundwater from the Sopron region.

Groundwater picks up radionuclides from the various rock types it passes through during its transport. Using the infrastructure of the radionuclide metrology team at JRC-Geel, Hungarian scientists analysed the low levels of natural radioactivity in groundwater samples.

The project helped Hungarian scientists develop a methodology to understand the dynamics of radionuclide uptake in groundwater. The **Sopron region** is regularly confronted with gross alpha activities exceeding the screening value of 0.1 Bq/L, which forces regulatory authorities to take action.

**Drinking water quality** measures revealed that drinking water of groundwater origin contained radionuclides in the surroundings of the metamorphic outcrop of the Sopron Mountains. Understanding the radioactivity phenomenon is crucial for **understanding its potential health impact.**



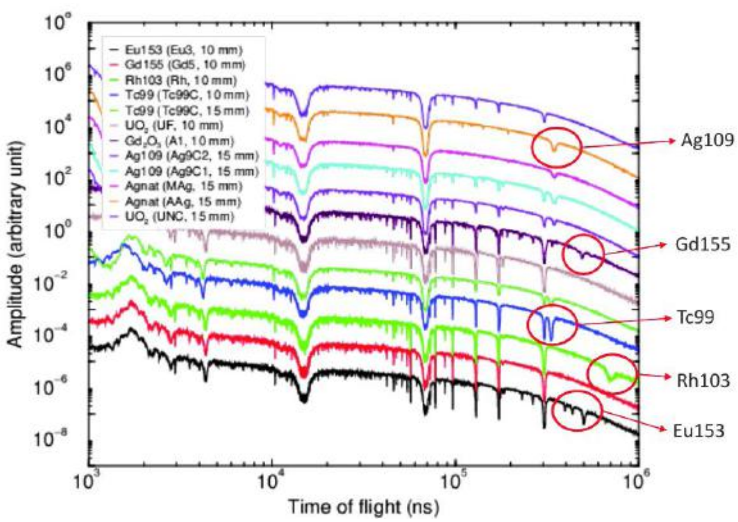

The location of the study area (a) and the sampling locations (b).

The JRC's Neutron Time-of-Flight Facility is one of the best pulsed white spectrum neutron sources available in the world

**Burnup credit** is a well-established and by safety authorities recognised approach for criticality safety evaluations at the back end of the fuel cycle, including the management of spent nuclear fuel.

The French approach takes advantage of reactivity loss due to the presence of non-fissile actinides and some strong neutron-absorbing fission products. To validate the codes and nuclear data used in the **criticality safety calculations**, dedicated pile oscillator measurements were performed in the zero-power reactor MINERVE (CEA Cadarache). The results of these experiments show substantial differences between the calculated and experimental reactivity worth, for example, for $^{103}$Rh, a difference of +10% was observed. These differences are most likely due to biases in the sample composition and/or nuclear data involved in the calculations. To clarify the differences, CEA Cadarache proposed a series of experiments at the **GELINA facility** as part of the MINERVE_BUC open-access project. Within this project, **Neutron Resonance Transmission Analysis (NRTA)** was applied at the GELINA facility to characterise the MINERVE samples, which include pellet samples made of natural and isotopically enriched materials of Tc, Rh, Ag, Cs, Nd, Sm, Gd, Eu, Dy Er, and Hf.

The results of the experiments at GELINA revealed the presence of tungsten impurities, which were not declared by the manufacturer of the samples. The presence of such strong neutron-absorbing materials has a strong influence on the results of pile oscillator measurements and partly clarifies the differences between the calculated and experimental results. The experimental program on MINERVE samples at the GELINA facility is still in progress. It will deliver results for at least 30 nuclides. The second phase of this program would concern MINERVE samples containing actinides.




Examples of raw data obtained with MINERVE samples containing $^{107}$Ag, $^{155}$Gd, $^{99}$Tc, $^{103}$Rh and $^{153}$Eu isotopes.

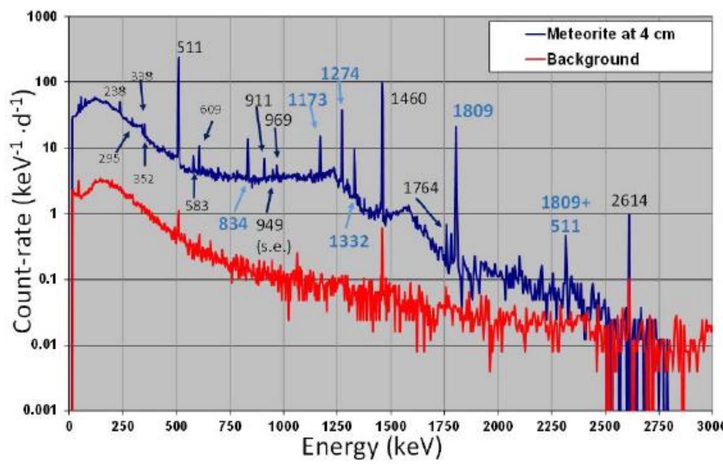
HaH 346 L6 meteorite weighing 488 g with an irregular shape

**Meteorites** are unique and scientifically invaluable objects used to study space and understand the solar system. When asteroids travel through space, they are activated by the cosmic rays. Many radionuclides are produced, but start to decay when meteorites hit Earth. These **cosmogenic radionuclides** thus act as clocks and can help establish, for example, the exact date of meteorite fall. Meteorites have been the focus of the open access project ACMET (Understanding the activation of meteoroids in space through gamma-ray spectrometry studies) which was carried out by POLATOM NCBJ, Poland.

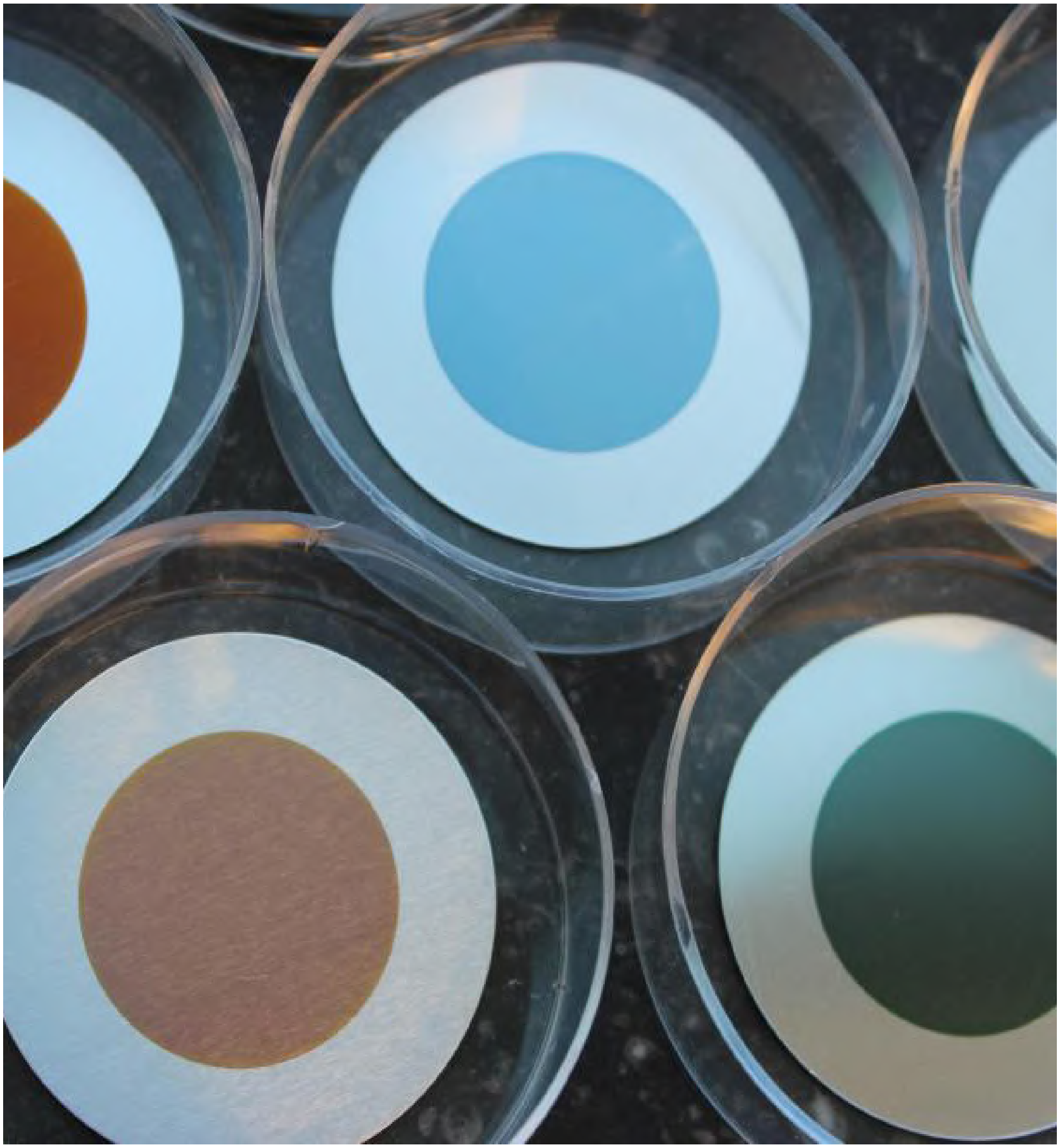
Scientists from POLATOM analysed a series of meteorite samples that fell in Libya in the Hammadah al Hamra region (HaH) in the **HADES underground laboratory**. This study made it possible to resolve the divergent observations of witnesses who observed meteorite falls. The majority of witnesses claim a fall date of 20 August–28, 2018; however, individual claims suggest the day of the fall on 14 November 2017.

Furthermore, the study also showed the possibility of establishing the size and mass before breakup using radionuclide data. In addition, drill cores were taken from two other meteorites and analysed for radioactivity. This is because activation inside a meteoroid changes with depth and depends on the size of the meteoroid. In these two cases, no significant change could be detected in the $^{26}$Al-massic activity; however, this information was useful as it helped establish the location of the meteorite fragment within the original meteoroid.

The underground gamma-ray spectrometry of the HaH 346 meteorite fragment resulted in the detection of six cosmogenic radionuclides. Analyses of $^{22}$Na, $^{26}$Al, and $^{60}$Co massic activities clearly indicated the date of fall in August 2018.




The gamma-ray spectrum from the meteorite measurement at a distance of 4 cm from the detector (blue curve) and the background of the detector (red curve). The given numbers represent the gamma peaks in keV. The light-blue numbers indicate the activation products.



Nuclear Target Preparation Laboratories at JRC Geel

The JRC produces and characterises a variety of targets for high-precision measurements of neutron-reaction data at the GELINA and MONNET accelerators. The **targets** are thin stable deposits of $^{6,7,nat}LiF$, metallic Li, $^{10}B$, tristearine or thin actinide deposits of U, Pu, Np or Am isotopes, on a thin metallic or plastic foil. These deposits need to be homogeneous, mechanically stable and well characterised for their isotopic composition, mass and areal density. Other samples like metallic disks, wires, alloys and powder compacts are also prepared.


The set-up at GELINA for detecting neutron capture reactions in nuclear measurements

Cross-sections for neutron interactions with Zr and Mo isotopes are important for nuclear energy technology and nuclear astrophysics. Zirconium, as a structural material, and Mo isotopes, produced as fission products, are important nuclides for criticality safety analysis. The use of Mo for the production of ATF is under study, and Mo is considered a promising candidate for new-generation research reactors based on UMo alloys with Low Enriched Uranium. Cross-sections for neutron capture reactions with Zr and Mo isotopes play a crucial role in nucleosynthesis, that is, understanding the production of elements heavier than iron. The most relevant cross-sectional data in the evaluated nuclear data libraries are recommended with large uncertainties. To improve the status of the experimental data and to allow for a new evaluation, transmission and capture cross-section measurements were performed at the GELINA facility using natural and isotopically enriched Zr and Mo samples. The results of these measurements were used in a resonance shape analysis together with complementary capture cross-section data obtained from measurements at the n_TOF facility at CERN to derive improved resonance parameters for $^{92}$Zr and $^{92,94,95,96,97,98}$Mo. Part of the experimental data was submitted to the EXFOR data library, and the results of the Mo-isotopes were adopted in the latest JEFF-evaluated data library.

# Provide evaluated nuclear data and recommendations to the Joint Evaluated Fission and Fusion (JEFF) project for nuclear technology applications within EU MSs

JRC's Neutron Time-of-Flight Facility (GELINA)

# Nuclear data

## Global coordination efforts on nuclear data and direct support to MSs organisations

Ten $^{239}Pu$ thin deposits with a total mass of approximately 10 mg were successfully prepared at JRC Geel by molecular plating on a thin aluminium foil. The $^{239}Pu$ alpha activity was determined by alpha-particle counting at a defined solid angle. In addition, a thick sample with a total mass of 100 mg $^{239}Pu$ was encapsulated in an aluminium container. The atomic abundances of the Pu base material were analysed using thermal ionisation mass spectrometry. Prior to target preparation, the Pu material was purified for $^{241}Am$ at SCK CEN Belgium. The $^{239}Pu$ thin deposits were mounted in an ionisation chamber to measure the α-ratio and (n,γ) cross-section of $^{239}Pu$ at JRC Geel and at n_TOF in CERN. The 100 mg $^{239}Pu$ sample was used in another experimental setup to extend the measurement to higher neutron energies. This activity is part of the scientific program approved by the Euratom H2020, which supplies accurate nuclear data for energy and non-energy applications – the SANDA project. CIEMAT Spain, University of Lodz Poland and JRC-Geel Belgium were involved. More accurate $^{239}Pu$ capture and fission cross-section data are needed for the operation of fast reactors and thermal reactors and have been listed in the NEA/OCDE high-priority request list.

The set-up at GELINA for measuring the influence of sample temperature on neutron transmission.

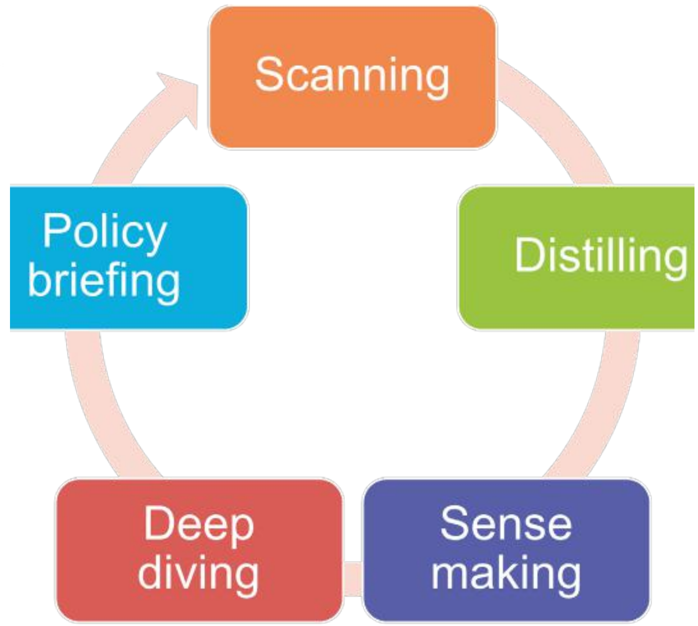
# FORESIGHT …

# Knowledge Activities

08

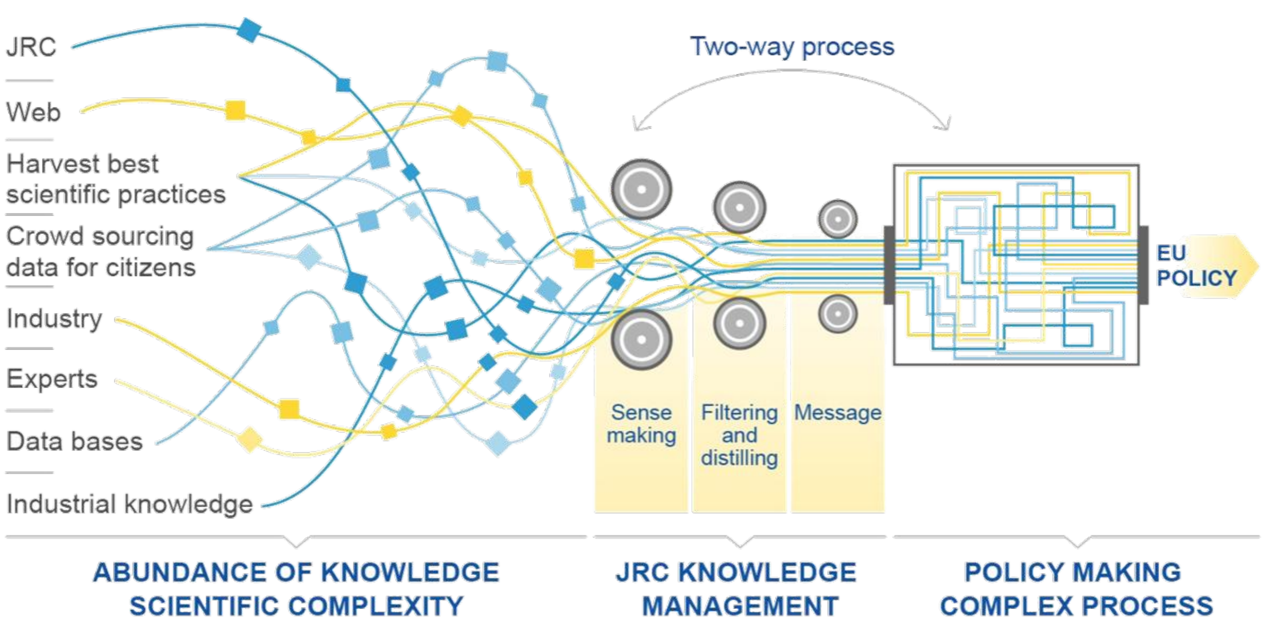
## define and implement a methodology of horizon scanning for foresight

The JRC is committed to providing scientific knowledge and technical support to European Union policies, particularly those related to nuclear technology. The JRC's anticipatory capabilities are crucial for providing timely evidence-based advice to policymakers. The Euratom Foresight cycle developed at the JRC consists of five distinct activities: scanning, distilling, sense making, deep diving, and policy briefing. The three first steps: scanning, distilling and sense making compose the yearly process of Horizon Scanning for Euratom. Through foresight methodologies, 11 critical topics for the future of nuclear technology in the EU were identified. They range from the resurgence of nuclear start-ups to the potential for nuclear technology to aid in decarbonising hard-to-abate sectors and integrating digital technologies into the nuclear sector. Emerging trends in nuclear technologies, emphasising their potential threats and opportunities in the 2033 and 2053 horizons, provide a roadmap for policy consideration in this field.




Euratom Foresight Cycle

"To make sense of the abundant information and feed it to policy makers"



## Nuclear for abating the hardest-to-abate

Industrial sectors collectively account for nearly 30% of global emissions

Industrial process heat production
mobile micro-reactors as large batteries
low carbon hydrogen production

## Nucle

New tech
(digitalisa

New way
and proto

## Euratom lessons for a 'EurAI'

safe and responsible use of AI technology

## Nucle

**Revival** of the
the introductio

- Comp to the in Eur
- Start- scala prese nucle
- Start- and t result strea

## Nuclear Fuel Strategic Autonomy

Europe's dependence on Russian nuclear fuel

Europe must increase its production capacity

Efficient use of resources (i.e. fast reactors, Pu)

## Technology & Talent for LTO

deployment of new technologies and fostering of a new generation of nuclear professionals

## ar 2.0

nologies
ation)

s of designing
otyping

## Nuclear fuelling a circular economy

reuse and recycle radioactive materials

## Atoms for Space

Reinforcing Europe's competitiveness through space

Nuclear reactors for space exploration

## (Nu)clearing the digital carbon footprint

nuclear energy to clear the carbon footprint of the digital infrastructure

## ear (re)start-up

**nuclear industry** primarily due to
n of **Small Modular Reactors** (SMRs)

act and innovative SMRs have led
e emergence of several start-ups
rope
-ups leverage the versatility and
bility of SMRs to enhance their
nce and diversity within the
ar industry
-ups incorporate digital tools
echnologies into their designs,
ing in a more efficient and
mlined development process

## The grid sustaining the green energy mix

Nuclear as reliable baseload

Nuclear reactors can support hydrogen co-generation

## The environmentalist nuclear choice

Smaller physical footprint, no air pollution, continuous supply of power, independent of weather conditions

# Critical Questions

Nuclear technology development

Eur

* To
* Ho
* W
* Sh
* Ca
* W
* Ho

Five concrete topics raise critical questions that deserve further attention

Misin

* Are th of nu
* How c
* Can p the to

## ropean SMR Fuel Strategic Autonomy

o what extent are we dependent on Russia for the HALEU fuel that Advanced Modular Reactors might be using?
ow is global uranium supply expected to evolve in the following years?
/hat is the current state of European fuel conversion, enrichment, and assembly facilities?
hould this be a European or just a national concern?
an fuel producers start developing a whole production line for a new product without knowing even if there would be a client?
/hat could be the impact of the absence of HALEU production capacity over the number of deployable SMR concepts?
ow is the US handling their own dependence towards Rusia?

## The challenges of the construction of SMR demonstrator projects

* What are the main challenges for the construction of SMR demonstrator projects: funding, licensing,
* Access to a licenced facility, nuclear fuel, and recruitment of skilled workers?
* How can Euratom facilitate the construction of SMR demonstrator projects?
* What are the incentives for private/public investors to participate in the construction of SMR demonstrator projects?

## SMRs power critical infrastructure

* What are the main nuclear micro-reactor specific features required by critical infrastructure such as hospitals, water purification, transportation, and communication networks
* To what extent can datacenters be considered critical infrastructure?
* Have nuclear micro-reactors and data centres similar needs in terms of security, reliability or decommissioning?
* Would it make sense to place a nuclear-powered data centre at the bottom of the ocean? and on the moon?

## Skilled nuclear workforce

* To what extent could automation mitigate the scarcity of skilled nuclear workers constraining the European industry?
* Could innovative education and training strategies, such as those applied by big tech to speed up the deployment of their technologies, have a similar success in the nuclear industry?
* In what position does the European Union attract talent beyond its borders with respect to other OECD countries?
* To what extent would the deployment of nuclear reactors in embarking countries have a positive effect on increasing the available pool of nuclear expertise worldwide?

## nformation and disinformation about nuclear energy

ne planned and targeted actions of malicious foreign actors to damage the reputation
clear technology in the EU undermining the competitiveness of its industry?
can they be measured or monitored?
oublic administration intervene effectively in the subject, given the high sensitivity of
opic?

More people **support the use of nuclear energy** than oppose it (Radiant Energy Group, 2023).

# Public Attitudes Nuclear 2023

The last Eurobarometer on nuclear energy production, conducted in 2008, showed that public opinion was strongly divided in the European Union. Nearly identical shares of respondents expressed support for nuclear energy (44%) and opposition (45%). Citizens in countries with operational nuclear power plants were more likely to support nuclear energy.

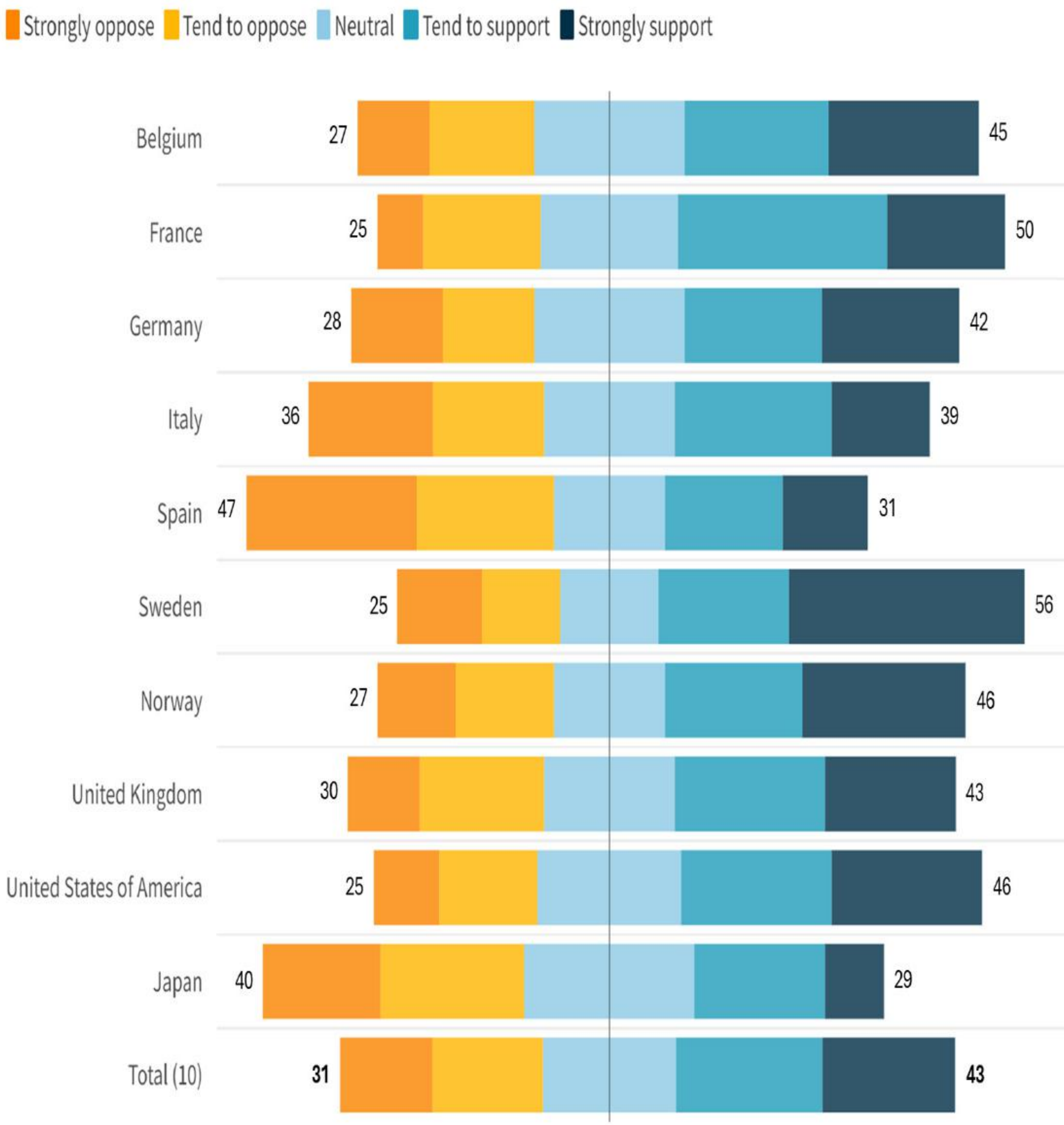
New studies on the public's perception of clean energy sources and the factors shaping these perspectives were published in 2023. All surveys showed a substantial shift in European opinion towards nuclear energy, influenced by the Covid-19 pandemic, conflict in Ukraine, and interventionism from China and the USA. Recent changes in European energy policy, such as joint gas purchasing, energy demand reduction targets, storage obligations, and a focus on renewables, highlight a move towards more collaborative and coordinated approaches at the EU level. The renewed credibility of nuclear energy in Europe, prompted by discussions on green taxonomy and the need for energy security, has led to a reassessment of the nuclear energy's place within the energy mix.

Four elements—renewables, nuclear, gas, and efficiency/sobriety—create a new energy landscape that outlines four potential avenues of action within the dual framework of decarbonising economies and enhancing Europe's energy independence. They also set boundaries for possible energy mixes within which Member States can shape their national energy policies.

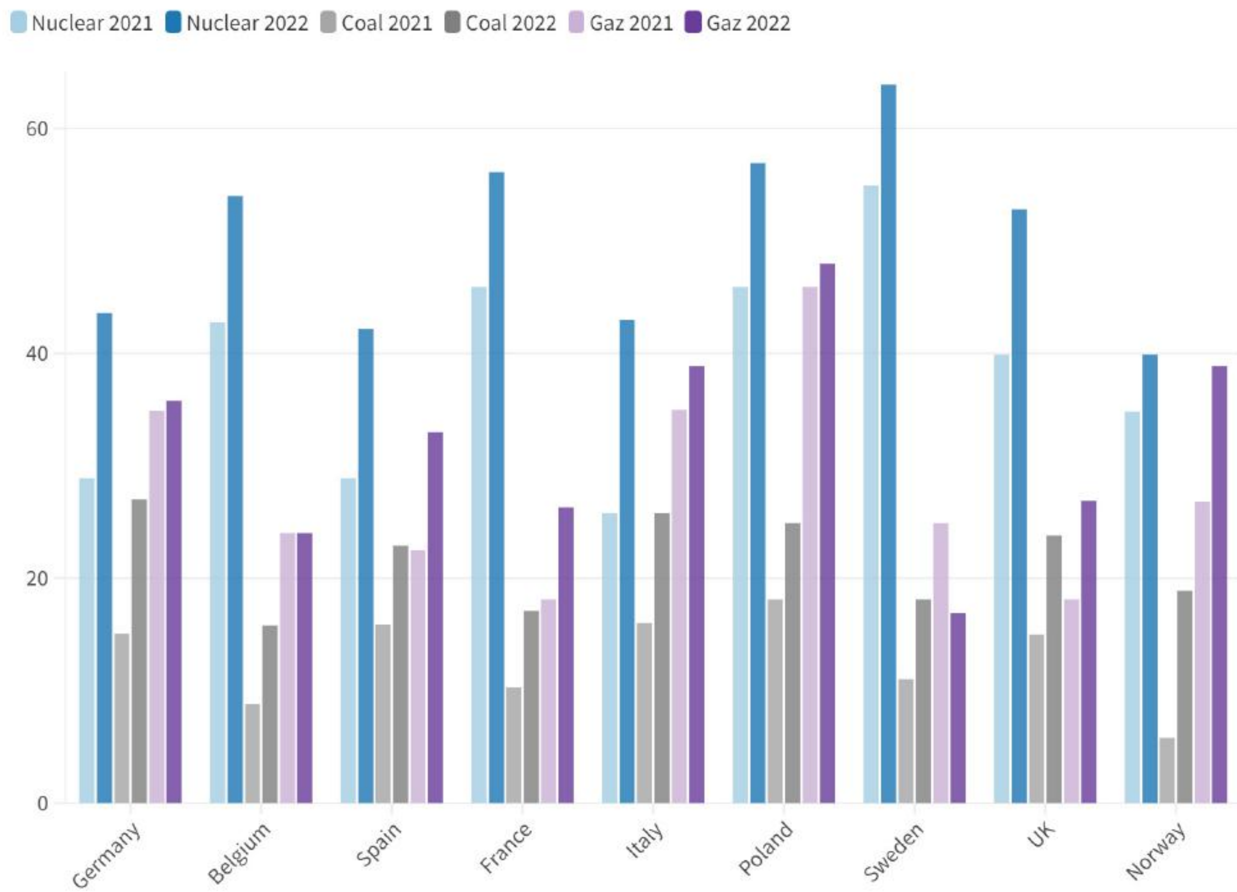
A summary of new findings on public opinion in some European Member states and third countries with respect to clean energies are presented and discussed in this chapter.

The Public Attitudes Toward Clean Energy Index 2023 covers 20 countries. The survey was conducted by Savanta and commissioned and analysed by the Radiant Energy Group. We focused our analysis on the EU members covered by this study, as well as Norway, the UK, the USA, and Japan.

Across our selection of countries, 31% of survey respondents opposed the use of nuclear energy while 1.4 times more (43%) supported it. Eight of the ten selected countries surveyed had net support (support exceeding opposition) for nuclear energy use. Support is approximately double that of opposition in the EU member states surveyed, except for Spain. It also highlights the support for the use of nuclear technology in countries that do not use it (Italy and Norway) or have recently phased out its use (Germany). Finally, in Japan, opposition to nuclear energy exceeds the support.




% of people that oppose or support nuclear energy use in their country.
Data extracted from Radiant Energy Group.

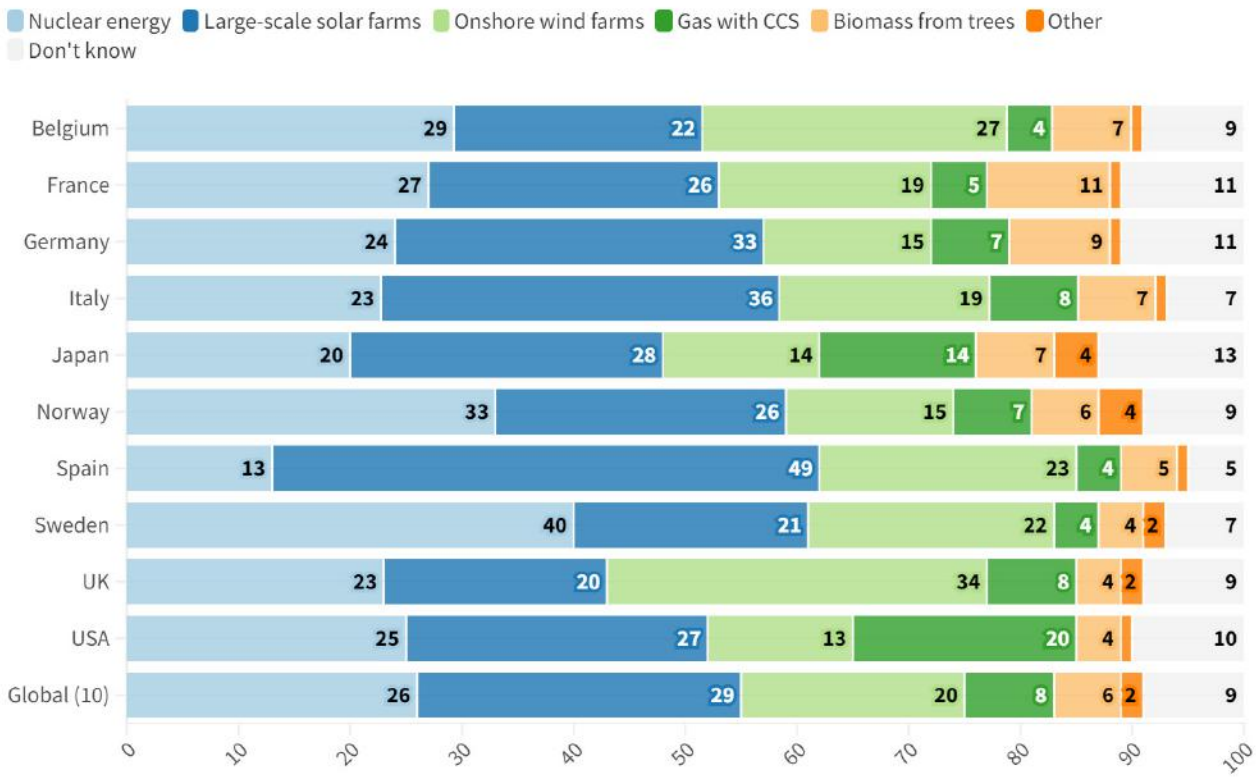



Trends in support (%) for different modes of electricity generation (data source: [Robert Schuman Foundation]).

Similar results are reported in the study conducted by the Robert Schuman Foundation and published in 2023.

This study shows that, regardless of the countries' decisions on nuclear power (new build or phase out) by 2022, there was a net increase in support for nuclear energy. This increase is particularly strong in countries where anti-nuclear opinion is predominant and entrenched, such as Italy (+18 points) or Germany (+15 points), and more moderate but notable in countries committed to a nuclear phase-out path, such as Belgium (+12 points) and Spain (+13 points). The United Kingdom, which has embarked on a new nuclear program, has seen a stronger increase (+14) than France, where support for nuclear power in September 2021 was already high.

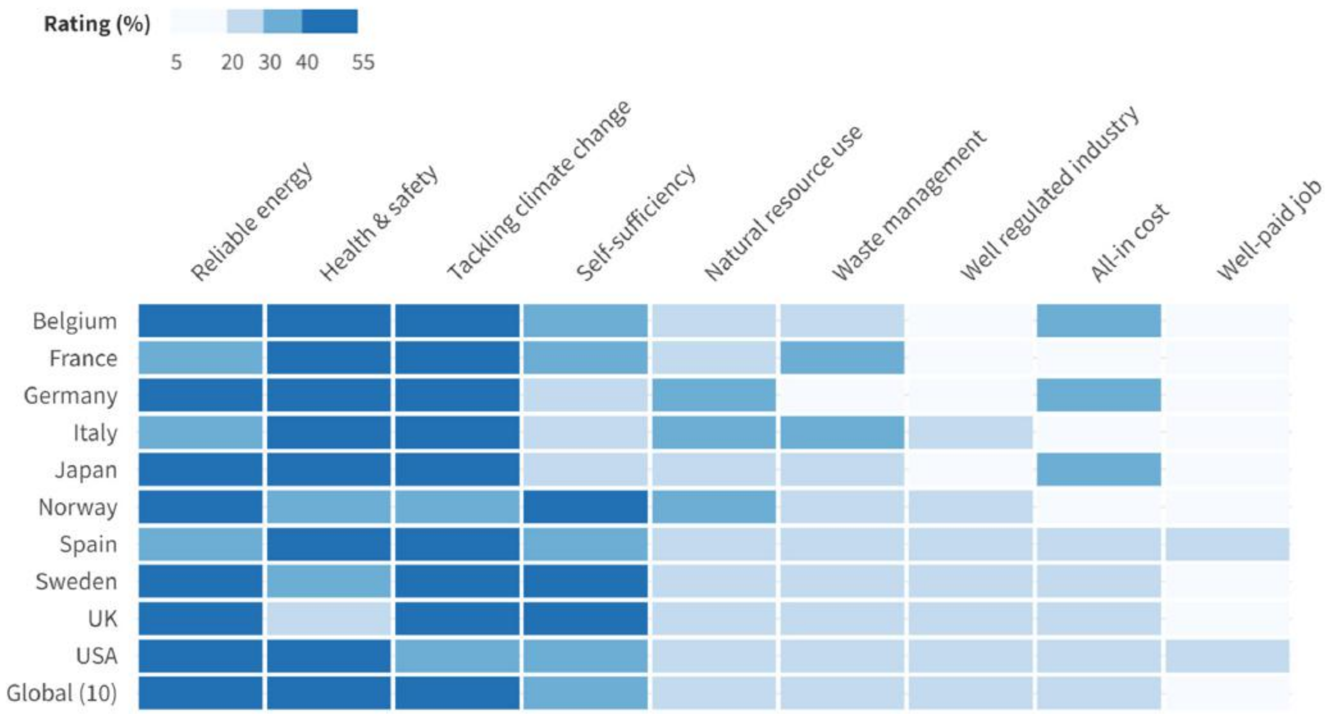
The swift transformations can be attributed to the war in Ukraine, as it focuses on public opinion, media attention, and political representatives on energy issues, primarily because of the conflict's impact on energy costs, inflation, and European purchasing power.




Respondents' considerations on which type of energy should be prioritised by their country when considering a change in the existing energy mix generation (data from the Radiant Energy Group).

This situation has revitalised the interest in a diversified energy mix and production sources that have been previously overlooked.

These developments have taken place to the detriment of opinions that are opposed to nuclear power, particularly in countries that have historically been hostile to this type of energy, such as Germany and Italy. In all of these European countries, public support for renewable energy (RE) is strong. The support for solar power is particularly high in Spain, Italy, and Germany. UK support for wind energy is higher than elsewhere, whereas France and Germany are less supportive of this energy. Norway has a substantially high preference for nuclear energy use in a country that does not use nuclear energy to generate electricity. Globally, across the selected 10 countries, nuclear energy is the second most preferred electricity source after large-scale solar farms. Of those surveyed, 26% said that their country should focus on nuclear energy, behind only 29% of their preferences for large-scale solar farms. The preference for nuclear energy is larger than for onshore wind, biomass from trees, or gas with carbon capture and storage (CCS). There is also a preference for nuclear energy over gas with CCS in some oil and gas exporting countries, such as the USA and Norway.




An overview of the energy attributes, respondents saw as the most important to their country's future energy needs (data from the Radiant Energy Group).

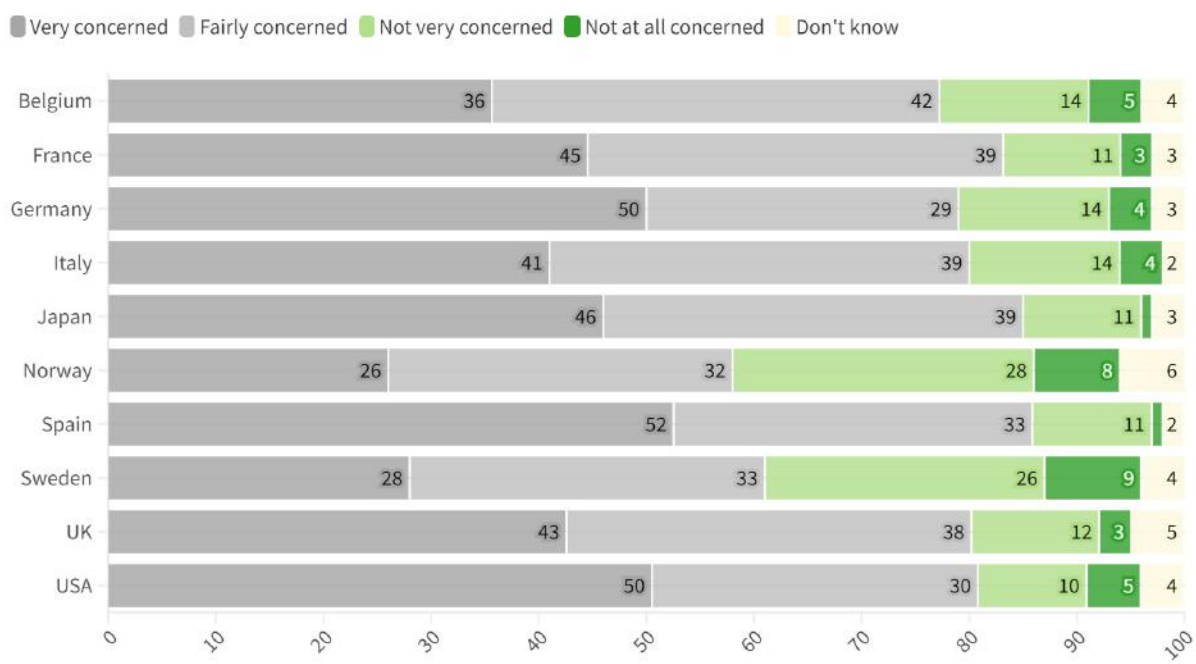
When survey participants were asked which energy attributes were most important to their country's future energy needs, globally, across the selected 10 countries, **reliability** was the public's highest-priority energy attribute.

Most respondents rated reliability, health and safety, and tackling climate change as their top three most important considerations when providing for their country's future energy needs. The importance of all-in cost (i.e. cost of infrastructure, cost to consumers) is strongest in Germany and Belgium, two of the countries most severely impacted by the recent post-2020 energy crisis. The significance of achieving self-sufficiency (i.e. not needing to import energy) is particularly high in Sweden, Norway, and the UK.

Nuclear reliability was well perceived in most countries (more than 50% of respondents), with the exception of Italy and Spain, where large solar farms and onshore wind farms were considered more reliable. In the other selected countries, “Most respondents seek **reliable energy** sources that benefit both their **health** and the **environment**”

nuclear reliability was ranked second or third regarding large-and onshore wind farms. In most countries nuclear is seen as more reliable than gas and biomass (data not shown).

Although there is considerable support for nuclear energy, there are also significant concerns that need to be addressed to gain wider acceptance, such as the **disposal and handling of nuclear waste**. In all the selected countries surveyed, the majority were concerned about nuclear waste. Norway and Sweden have more positive global perceptions than the other selected countries. Indeed, Norway does not have a nuclear program, and Sweden has an advanced program for a final geological repository. France is the world leader in nuclear waste recycling, with 10% of its nuclear electricity originating from nuclear waste, and has an advanced program for a final geological repository. However, France’s efforts to address this issue have not differentiated its public concern for nuclear waste from those of other countries.



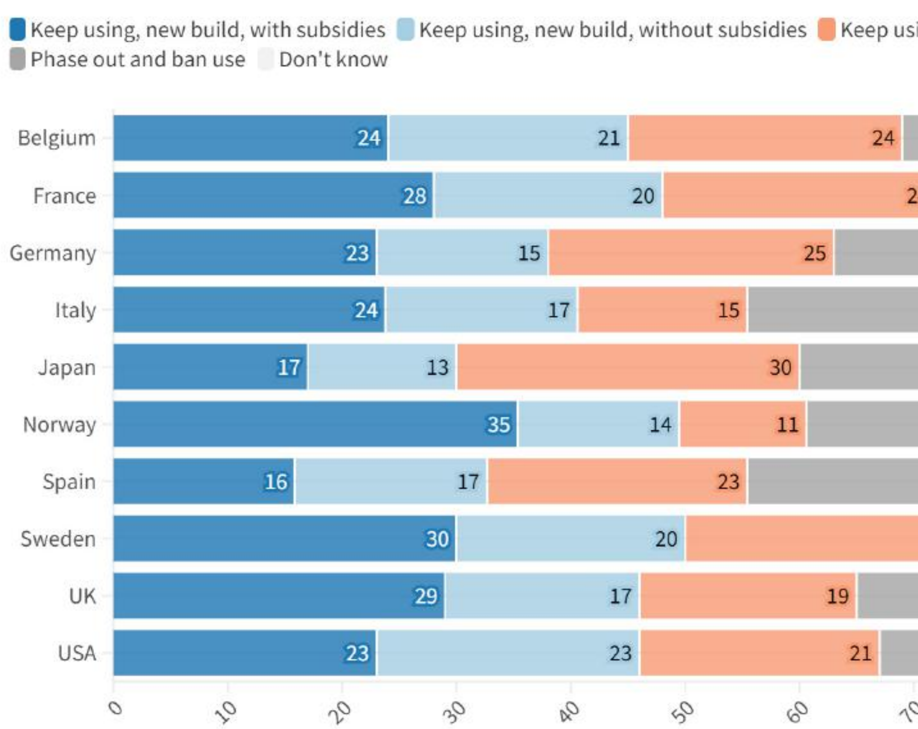

Level of concern (%) among respondents regarding waste management associated with nuclear energy.

data from the Radiant Energy Group

# "Globally, the support for nuclear approximately the double than the

The nuclear sector is characterised by substantial capital investment, stringent regulations, and long-term operational horizons. Considering these industry dynamics, it is crucial for governments to provide stable policy support to ensure the success of nuclear projects. As the public interest is a key consideration for policymakers, it is essential for them to comprehend the public's preferences regarding nuclear energy policy. Within nuclear-powered countries, two-thirds of the respondents want to keep using nuclear power rather than phase it out, apart from Spain, which only represents half. Within the three countries without existing commercial reactors (Italy, Norway, and Germany), the same results were observed; more than 56% of respondents wanted to build new nuclear power plants rather than ban their use. While support or opposition indicators offer a glimpse of public sentiment, they do not accurately

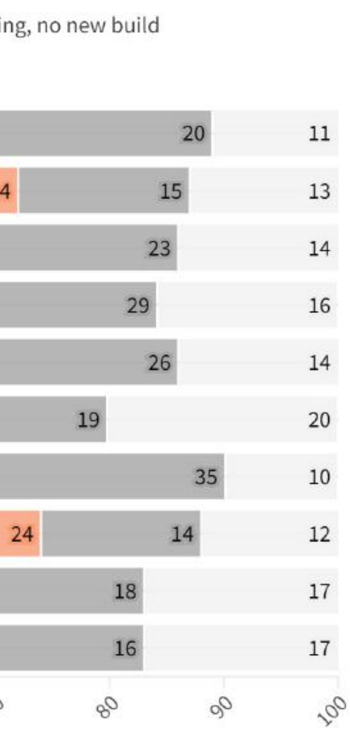
Which policy approach do you think your country should adopt for nuclear energy?
(data from Radiant Energy Group, %)



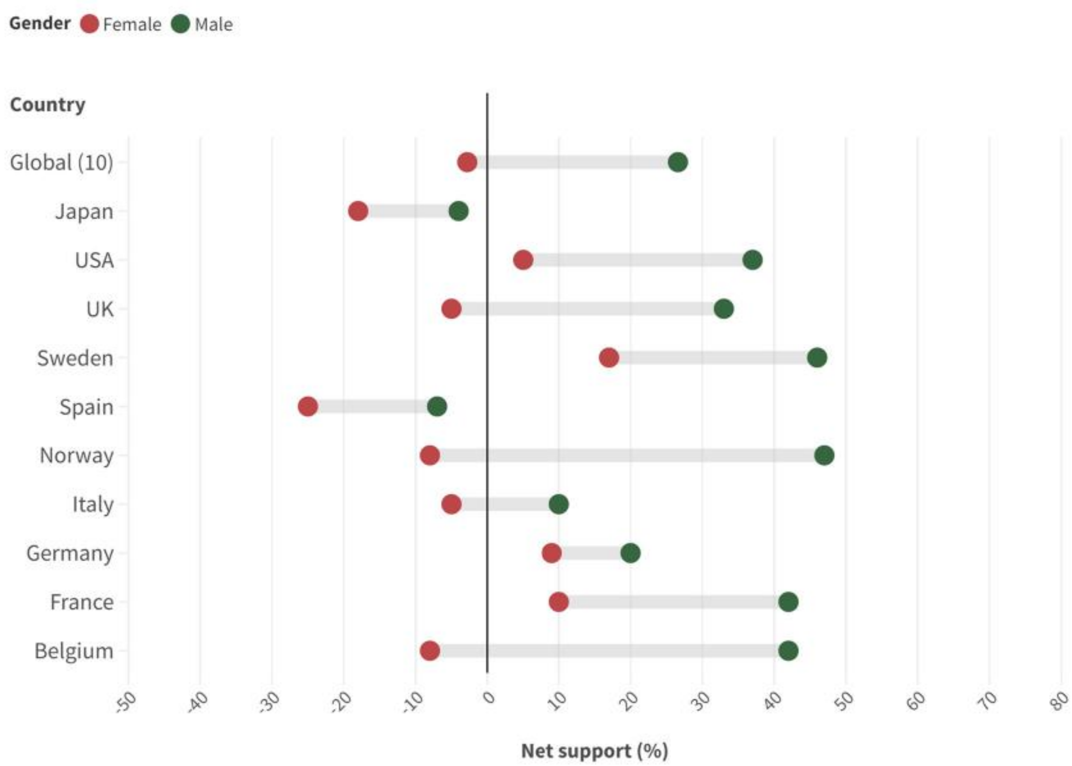
new builds is
e desire to ban its use”

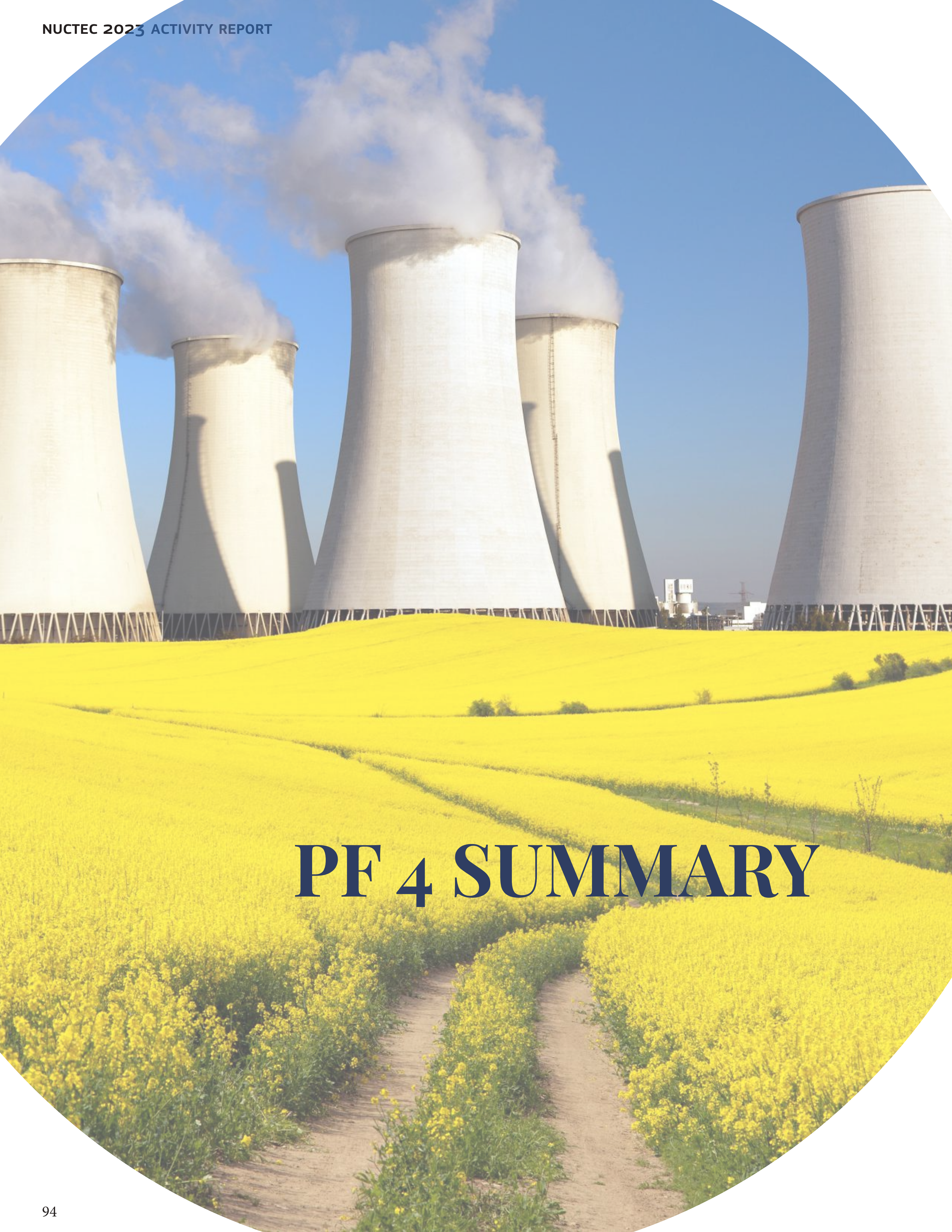
reflect public preference for government action. 75% of people supporting nuclear power use wish for their government to build new nuclear power plants. While those who tend to oppose nuclear energy have less support for new nuclear builds, 54% of this group support policies to keep operating existing nuclear plants and 17% wish for governments to build new nuclear plants.

Gender consistently divides nuclear support. Male demographics were consistently the most supportive of nuclear energy use. No data are available yet, but it would be interesting to know the causes of this gender variation in net support for nuclear energy and whether the same variation occurs in other technologies.




Gender net support (total support – total opposition) for the use of nuclear energy in their country, %



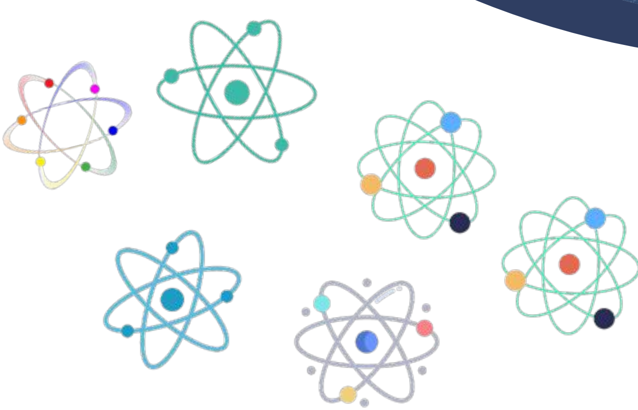


# PF 4 SUMMARY

As part of the JRC work programme 2023-2024, this science for policy report covered the achievements of PF4. It highlighted the JRC research efforts in the field of safety of the nuclear life cycle, radioactive waste management and disposal, radioactivity in the environment, nuclear applications, open access and nuclear data, and knowledge management and foresight. These core scientific areas are of interest for developing and improving safety standards for nuclear technologies, including advanced waste-minimising technologies and new nuclear energy generation projects. The report does not encompass the entirety of PF4's project results but is a noteworthy demonstration of the JRC's scientific excellence. Special recognition is given to dedicated efforts toward developing the next generation of nuclear scientists and engineers.

PF4 ensures continuity between short- and long-term research and competences in the context of the energy transition and decarbonisation of the EU economy by 2050 through several research activities which are the backbone of implementating the direct actions of the Euratom research and training programme in the areas mentioned above. PF4 evolution in the next work programme cycle could benefit from aligning project objectives with strategies of relevant European networks such as SNETP and IGDTP and establishing more complementarity with Member States' national research programs. This alignment can lead to a consolidated and impactful portfolio.

In light of the new Commission guidelines for 2024-29, under the political guideline heading "**A new plan for Europe's sustainable prosperity and competitiveness**", the proposal for a **new clean industrial deal**, **research and innovation** at the heart of our economy and **tackling skills and labour gaps**, there are new opportunities to build on an independent European nuclear supply chain and the needs implied by the revival of the European nuclear industry, particularly in terms of skills and innovation.



# ANNEXES

| Domain | Project | Indirect Act |
|---|---|---|
| Safety of the Nuclear Life Cycle | COFIS | Accelerated Program for Implementation of secure VVER fuel |
| | COFIS | SiC composite claddings: LWR performance optimization for n |
| | ASME | Proof of Augmented Safety Conditions in Advanced Liquid-Me |
| | ASME | Partitioning And Transmuter Research Initiative in a Collabora |
| | ASME | Fuel Recycle and Experimentally Demonstrated Manufacturin |
| | AREIN | Plutonium Management for More Agility |
| | AREIN | MultI-recycling strategies of LWR SNF focusing on MOlten SAl |
| | AREIN | Severe Accident Modeling and Safety Assessment for Fluid-fu |
| | F4SMR | Reduction of Radiological Consequences of Design Basis and |
| | F4SMR | OPEn HPC theRmomechanical tools for the development of eA |
| | INVISION | Innovative Structural Materials for Fission and Fusion |
| | INVISION | NUclear COmponents Based on Additive Manufacturing |
| | INVISION | Organsation of the European Research Community on Nuclea |
| | RAY | MultI-recycling strategies of LWR SNF focusing on MOlten SAl |
| | RAY | Partitioning And Transmuter Research Initiative in a Collabora |
| | RAY | Plutonium Management for More Agility |
| | RAY | Jules Horowitz Operation Plan 2040 |
| | SALTO | Management and Uncertainties of Severe Accidents |
| | SALTO | INcreasing safety in NPPs by Covering gaps in Environmental<br>ry data and component SCALE |
| | SALTO | STRUctural MATerials research for safe Long Term Operation |
| Radioactive waste management & disposal | FLAME&CO | European Joint Programme on Radioactive Waste Manageme |
| | SAILOR | European Joint Programme on Radioactive Waste Manageme |
| | SAILOR | Predisposal Management of radioactive waste |
| Radioactivity in the Environment | HERM | Awareness and resiliance through European multi-sensor syst |
| Nuclear Applications | SPA | PU-238-coupLed dynamic power system for SpAce exploRatio |
| Nuclear Data / Open Access/ E&T | ACTUSLAB | eurOpean platForm For accEssing nucleaR R&d facilities |
| | INVISION | eurOpean platForm For accEssing nucleaR R&d facilities |
| | EUFRAT | Building European Nuclear Competence through continuous A |
| | GEMSTONE | Supplying Accurate Nuclear Data for energy and non-energy A |

| tion Title | IA Acromyn | HR effort (PM) | End date |
| --- | --- | --- | --- |
| Supply | APIS | 1 | Jan-26 |
| ominal and accident conditions | SCORPION | 10 | Feb-28 |
| tal-Cooled Systems | PASCAL | 3 | Oct-24 |
| tive Innovation Action | PATRICIA | 4 | Aug-24 |
| g of Advanced Nuclear Solutions for Safety | FREDMANS | 5 | Aug-26 |
| | PUMMA | 16 | Sep-24 |
| t technology | MIMOSA | 5 | May-26 |
| el Energy Reactors | SAMOSAFER | 3 | Dec-23 |
| Design Extension Accidents | R2CA | 3 | Dec-23 |
| Atf fuels | OPERAHPC | 1 | May-27 |
| | INNUMAT | 5 | Aug-26 |
| | NUCOBAM | 9 | Sep-24 |
| r Materials | ORIENT-NM | 1 | Mar-23 |
| t technology | MIMOSA | 8 | May-26 |
| tive Innovation Action | PATRICIA | 4 | Aug-24 |
| | PUMMA | 1 | Sep-24 |
| | JHOP2040 | 3 | Sep-23 |
| | MUSA | 2 | May-23 |
| Fatigue Assessment - focusing on gaps between laborato- | INCEFA SCALE | 8 | Sep-25 |
| of LWR NPPs | STRUMAT-LTO | 4 | Aug-24 |
| nt | EURAD | 26 | May-24 |
| nt | EURAD | 1 | May-24 |
| | PREDIS | 3 | Aug-24 |
| tem | ARTEMIS | 2 | Sep-26 |
| n and beyond | PULSAR | 8 | Aug-24 |
| | OFFERR | 4 | Aug-26 |
| | OFFERR | 3 | Aug-26 |
| dvanced and Structured Education and Training Actions | ENEN2PLUS | 4 | May-26 |
| Applications | SANDA | 4 | Aug-24 |

### APIS

Horizon Europe

**Domain:** Safety of alternative nuclear fuel for VVER reactors
**Title:** Accelerated Program for Implementation of secure VVER fuel Supply
**JRC Contribution:** Advanced fuel performance modelling (considering Advanced Technological Fuels, advanced uncertainty analysis and code calibration, code coupling)

### ARTEMIS

Horizon Europe

**Domain:** Nuclear science and ionizing radiation applications, radiation protection, emergency preparedness
**Title:** Awareness and resiliance through European multi-sensor system
**JRC Contribution:** Testing of newly developed Rn-probes, organisation of ILC. Provision of input on environmental radioactivity and metrology.

### ENEN2PLUS

Horizon Europe

**Domain:** Education, training and mobility
**Title:** Building European Nuclear Competence through continuous Advanced and Structured Education and Training Actions
**JRC Contribution:** Supervision of PhD students. Organise and provide TRANSURANUS training course in Kalrsruhe

### EURAD

Horizon 2020

**Domain:** Safe spent fuel and radioactive waste management
**Title:** European Joint Programme on Radioactive Waste Management
**JRC Contribution:** Verification of nuclear waste inventories in irradiated nuclear fuel using innovative non-destructive detection methods Assessment of the response of nuclear fuel during extended interim storage to mechanical solicitations Knowledge Management

### FREDMANS

Horizon Europe

**Domain:** Safety of advanced and innovative nuclear designs and fuels
**Title:** Fuel Recycle and Experimentally Demonstrated Manufacturing of Advanced Nuclear Solutions for Safety
**JRC Contribution:** WP1 Advanced manufacturing. Evaluation of novel fuel synthesis methods, optimised for the (re-) fabrication of highly active fuels with improved properties and potentially added functionality, with a focus on nitride fuel.

### INCEFA SCALE

Horizon 2020

**Domain:** Safety of operating nuclear power plants and research reactors
**Title:** INcreasing safety in NPPs by Covering gaps in Environmental Fatigue Assessment - focusing on gaps between laboratory data and component SCALE
**JRC Contribution:** WP3: Test Program: Uniaxial tests and Data Management

### INNUMAT

Horizon Europe

**Domain:** Safety of advanced and innovative nuclear designs and fuels
**Title:** Innovative Structural Materials for Fission and Fusion
**JRC Contribution:** WP5: Qualification Methodology and Tests Standardization

### JHOP2040

Horizon 2020

**Domain:** Roadmap for use of Euratom access rights to Jules Horowitz Reactor experimental capacity
**Title:** Jules Horowitz Operation Plan 2040
**JRC Contribution:** WP3: Financial and Programme model for Euratom

### MIMOSA

Horizon Europe

**Domain:** Safe spent fuel and radioactive waste management
**Title:** MultI-recycling strategies of LWR SNF focusing on MOlten SAlt technology
**JRC Contribution:** MSR fuel and safety. Feasibility study of chloride salt irradiation in the HFR. Contribution in the definition of test matrix for out of pile corrosion and mechanical test.

### MUSA

Horizon 2020

**Domain:** Safety of operating nuclear power plants and research reactors
**Title:** Management and Uncertainties of Severe Accidents
**JRC Contribution:** Uncertainty Quantification: Application to in-reactor Severe Accident sequences. Applications to in-reactor SA sequences with an identification of the partners' different approaches and an illustration of the achieved results.

### NUCOBAM

Horizon 2020

**Domain:** Innovation for Generation II and III reactors
**Title:** NUclear COmponents Based on Additive Manufacturing
**JRC Contribution:** WP1 Methodology to qualify materials & components produced via additive manufacturing. WP3 Test programme: mechanical test programme by performing creep tests and stress corrosion cracking (SCC) tests (in AMALIA). Management of data with JRC materials database MatDB.

### OFFERR

Horizon Europe

**Domain:** Education, training and mobility
**Title:** eurOpean platForm For accEssing nucleaR R&d facilities
**JRC Contribution:** Provision and appropriate access to JRC's infrastructures

### OPERAHPC

Horizon Europe

**Domain:** Safety of operating nuclear power plants and research reactors
**Title:** OPEn HPC theRmomechanical tools for the development of eAtf fuels
**JRC Contribution:** WP3: Calculation of Input Data and Boundary Conditions Using State of the Art Fuel Performance Codes. WP5: Verification and Validation, Uncertainty and Sensitivity Analyses.WP6: Development of Improved Models for Industrial Fuel Performance codes.

### ORIENT-NM

Horizon 2020

**Domain:** Towards joint European effort in area of nuclear materials
**Title:** Organsation of the European Research Community on Nuclear Materials
**JRC Contribution:** Vision Paper. Materials for Sustainable Nuclear Energy: A European Strategic Research and Innovation Agenda for All Reactor Generations.

### PASCAL

Horizon 2020

**Domain:** Safety of advanced and innovative nuclear designs and fuels
**Title:** Proof of Augmented Safety Conditions in Advanced Liquid-Metal-Cooled Systems
**JRC Contribution:** WP1: Safety of the fuel pin system to assess the effectiveness of the fuel as first physical barrier. Task 1.2 Retention capacity of Cs, I, Te fission products in JOG and their diffusion in Pb and LBE using KEMS. Irradiated fuel-coolant interaction. Task 1.5 Irradiated fuel-coolant interaction

### PATRICIA

Horizon 2020

**Domain:** Safety of advanced and innovative nuclear designs and fuels
**Title:** Partitioning And Transmuter Research Initiative in a Collaborative Innovation Action
**JRC Contribution:** Feasibility study of transient test of fuel containing MA in the HFR. Small punch test of material exposed to lead. Development and implementation of new models and correlations in fuel performance codes (TRANSURANUS) for Am-bearing fuels. Code benchmarking.

**PREDIS**

Horizon 2020

**Domain:** Radioactive Waste Management
**Title:** Predisposal Management of radioactive waste
**JRC Contribution:** WP3 – Knowledge management

**PULSAR**

Horizon Europe

**Domain:** Nuclear science and ionizing radiation applications, radiation protection, emergency preparedness
**Title:** PU-238-coupLed dynamic power system for SpAce exploRation and beyond
**JRC Contribution:** WP1 Pu-238 Production and Processing. Production of PuO2 pellets with representative microstructure and their encapsulation. Contribution to the safety assessment of the handling and processing of Pu-238 in nuclear laboratories, as well as to the overall safety assessment, licensing and regulations.

**PUMMA**

Horizon 2020

**Domain:** Safety of advanced and innovative nuclear designs and fuels
**Title:** Plutonium Management for More Agility
**JRC Contribution:** WP6 – Education and training, dissemination and communication. Encourage mobility of PhD students, post-doc. Organize workshops for PhD students, post-docs, designers, and stakeholders, highlighting the issues related to FC scenarios, fuel behavior and spent fuel reprocessing. Improve educational tools (MOOC and data base) and learning methodologies.

**R2CA**

Horizon 2020

**Domain:** Safety of operating nuclear power plants and research reactors
**Title:** Reduction of Radiological Consequences of Design Basis and Design Extension Accidents
**JRC Contribution:** Development and implementation of new models in TRANSURANUS code for simulation of design basis accidents (LOCA) and steam generator break, development of new graphical user interface for statistical analysis (TUPython), development of interface for coupling of TRANSURANUS with SCIANTIX and MFPR-F codes for mechanistic modelling of fission gas behaviour.

**SAMOSAFER**

Horizon 2020

**Domain:** Safety of advanced and innovative nuclear designs and fuels
**Title:** Severe Accident Modeling and Safety Assessment for Fluid-fuel Energy Reactors
**JRC Contribution:** WP2 Fuel salt retention. WP3 Source term distribution and mobility. WP7 Education & Training and Dissemination & Exploitation

**SANDA**

Horizon 2020

**Domain:** Improved nuclear data for energy and non-energy modelling applications
**Title:** Supplying Accurate Nuclear Data for energy and non-energy Applications
**JRC Contribution:** Neutron induced fission cross sections at GELINA and n_TOF. Neutron capture measurements of stable isotopes at GELINA and n_TOF. Neutron inelastic cross section measurements on Pu-239,U-233, N-14 and Cl35,37. Branching ratio for Bi-209, Pb208 and U-238 cross sections.

**SCORPION**

Horizon Europe

**Domain:** Safety of operating nuclear power plants and research reactors
**Title:** SiC composite claddings: LWR performance optimization for nominal and accident conditions
**JRC Contribution:** WP7 – Advanced PIE of BR2-irradiated SiC-based ATF cladding materials.

**STRUMAT-LTO**

Horizon 2020

**Domain:** Safety of operating nuclear power plants and research reactors
**Title:** STRUctural MATerials research for safe Long Term Operation of LWR NPPs
**JRC Contribution:** Testing on previously irradiated materials and contribution to the validation of embrittlement trend equations and master curve approaches. The project is, to a large extent, the PIE of specimens from the joint JRC-NRG irradiation campaign LYRA-10, carried out in the HFR Petten from to 2007-2018. The JRC is involved in WP1, WP2, WP3, WP4, and WP5.

# GLOSSARY

| | |
|---|---|
| AAMs | Alkali Activated Materials |
| ALPS | Advanced Liquid Processing Systems |
| AM | Additive manufacturing |
| AMs | Advanced Materials |
| AMP | Ageing Management Programme |
| APIS | All Purpose Infusion Setup |
| ATF | Advanced Technological Fuel |
| BIPM | Bureau International des Poids et Mesures |
| CSS | Carbon Capture and Storage |
| DBA | Design Basis Accident |
| DEC | Design Extension Conditions |
| DEEP | Decay Data Evaluation Project |
| DPA | Displacement Per Atom |
| DSC | Differential Scanning Calorimetry |
| EDX | Energy Dispersive X-ray |
| ENIG | European Network for Inspection and Qualification |
| ENSDF | Evaluated Nuclear Structure Data File |
| EURAMET | European Association of National Metrology Institutes |
| FR | Fast Reactor |
| GND | Geometrically Necessary Disloca-tions |
| HBS | High Burnup Structure |
| ICRM | International Committee for Radio-nuclide Metrology |
| IG-DTP | Implementing Geological Disposal Platform |
| ISI | In-Service Inspection |
| ISOL | Isotope Separation On Line |
| JEFF | Joint Evaluated Fission and Fusion |
| KNC | Karlsruhe Nuclide Chart |
| LEU | Low-Enriched Uranium |
| LFR | Lead-cooled Fast reactor |
| LOCA | Loss of Coolant Accident |
| LOHC | Liquid Organic Hydrogen Carriers |
| LTO | Long Term Operation |
| LWR | Light Water Reactor |
| MBT | Membrane Bulge Test |
| MOX | Mixed Oxide |
| NDE | Non Destructive Examination |
| NDT | Non Destructive Testing |
| NPP | Nuclear Power Plant |
| NRTA | Neutron Resonance Transmission Analysis |
| PPMS | Physical Property Measurement System |
| RE | Renewable Energy |
| RHU | Radioisotope Heating Unit |
| RI | Research Infrastructure |
| RPS | Radioisotope Power Systems |
| RPV | Reactor Pressure Vessel |
| SEM | Secondary Electron Microscope |
| SGTR | Steam Generator Tube Rupture Accident |
| SMR | Small Modular Reactor |
| SNETP | Sustainable Nuclear Energy Technology Platform |
| SNF | Spent Nuclear Fuel |
| SSC | Structures, Systems and Components |
| TAT | Targeted Alpha Therapy |
| UHTC | Ultra High Temperature Ceramics |
| XPS | X-ray Photoelectron Spectroscopy |

# BIBLIOGRAPHY

## 01 Nuclear Energy 2023 in Review

### Data Sources

EU: nuclear fleet age 1970-2023 | Statista: https://www.statista.com/statistics/1352921/mean-age-of-nuclear-power-reactors-eu/
World Nuclear Industry Status Report 2023 (WNISR2023): https://www.worldnuclearreport.org/-World-Nuclear-Industry-Status-Report-2023-.html
IAEA: Source data: https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx
EMBER: Source data: https://ember-climate.org/insights/research/european-electricity-review-2024/#supporting-material
LowCarbonPower: https://lowcarbonpower.org/region/EU
National energy and climate plans: https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en

**International Energy Agency (IEA):** https://www.iea.org/reports/world-energy-outlook-2023

## 03 Safety of the Nuclear Life Cycle

### SALTO

Kolluri, M., et al., Structural Materials research on parameters influencing the material properties of RPV steels for safe long-term operation of PWR NPPs. Nuclear Engineering and Design, 2023. 406: p. 112236.

ENIQ position on Review of the current ENIQ suite of Documents on risk-Informed In-Service Inspection (RI-ISI) and Proposal of a Roadmap for RI-ISI Development. ENIQ report no. 69, 2023. https://snetp.eu/wp-content/uploads/2023/09/ENIQ_report_no_69_RI-ISI_Roadmap_final.pdf

MUSA Euratom H2020: Management and Uncertainties of Severe Accidents. Proceedings of the MUSA final workshop, 2023. https://musa-h2020.eu/wp-content/uploads/2023/05/Proceedings_MUSA_FinalOpenWorkshop.pdf

NDE in Nuclear 2023 Proceeding, Cuttlers' Hall, Sheffield, UK (27-29 June 2023). https://www.ndt.net/search/docs.php3?DocGroup=-1&MainSource=313

### RAY

van Til, S., et al., Irradiation performance and first examinations of Americium bearing blanket fuel from the MARINE irradiation experiment. Journal of Nuclear Materials, 2023. 587: p. 154699.

Cozzarizza, D., Benchmarking of Monte Carlo tools for modelling radiation damage induced by charged particles and neutrons in matter, Corniani, E., D`agata, E. and Giusti, V. editor(s), European Commission - Joint Research Centre, Petten, 2022, JRC131673.

### F4SMR

de Lara, A., et al., Towards preliminary design calculations with TRANSURANUS for application of Hastelloy cladding material. Annals of Nuclear Energy, 2023. 192: p. 109973.

Luzzi, L., et al., Assessment of INSPYRE-extended fuel performance codes against the SUPERFACT-1 fast reactor irradiation experiment. Nuclear Engineering and Technology, 2023. 55(3): p. 884-894.

Sanchez-Torrijos, J., et al., A review on the thermo-mechanical modelling needs in system codes. Nuclear Engineering and Design, 2023. 406: p. 112243.

Van Uffelen, P., A. Schubert, and Z. Soti. Assessing the Effect of Some ATF Materials and Uncertainties on Their Properties Under Normal Operation Conditions by Means of the Transuranus Code. in Proceedings of the 23rd Pacific Basin Nuclear Conference, Volume 3. 2023. Singapore: Springer Nature Singapore.

Zullo, G., et al., Towards simulations of fuel rod behaviour during severe accidents by coupling TRANSURANUS with SCIANTIX and MFPR-F. Annals of Nuclear Energy, 2023. 190: p. 109891.

**AREIN**

Geiger, E., Benes, O., Vigier, J., Boboridis, K., Robba, D., Colle, J., Cremer, B., Ernstberger, M., Poeml, P., Himbert, J., Gardeur, S., Lajarge, P., Popa, K., Boshoven, C., Vlahovic, L., Wiss, T., Piro, M.H. and Konings, R., Experimental validation of the TAF-ID: High temperature behaviour of simulated Ex-vessel corium and MOX-Lanthanides (Ce, Gd, La, Nd), Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/693912, JRC135045.

**COFIS**

Turnbull, J.A., et al., Effect of burn-up on the thermal conductivity of light water reactor fuel: Results of investigations employing the laser flash technique. Journal of Nuclear Materials, 2023. 580: p. 154398.

**FLAME&CO**

Luzzi, L., et al., Helium diffusivity in oxide nuclear fuel: Critical data analysis and new correlations. Nuclear Engineering and Design, 2018. 330: p. 265-271.

Pizzocri, D., et al., A modelling methodology for the description of helium behaviour accounting for the grain-size distribution. Nuclear Engineering and Design, 2023. 411: p. 112426.

Rondinella, V.V., et al., Research activities on radioactive waste management and on the back end of the nuclear fuel cycle performed by the Joint Research Centre of the European Commission. Il Nuevo Cimento, 2023. 46(C): p. 38.

Wiss, T., et al., Impact of alpha-damage and helium production on Heat Capacity of (U, Pu)O2, in 30th general conference of the Condensed Matter Division of the European Physical Society. 2023: Milano, Italy.

## 04 Radioactive Waste Management & Disposal

Radioactive waste and spent fuel: https://energy.ec.europa.eu/topics/nuclear-energy/radioactive-waste-and-spent-fuel_en

**SAILOR**

García-Gómez, S., et al., Molybdenum release from high burnup spent nuclear fuel at alkaline and hyperalkaline pH. Nuclear Engineering and Technology, 2024. 56(1): p. 34-41.

Milena-Pérez, A., et al., Spent Nuclear Fuel oxidation under dry storage controlled conditions for studying its radial oxidation behavior. Journal of Nuclear Materials, 589, 2024, 15483. https://doi.org/10.1016/j.jnucmat.2023.154831.

Iglesias, L., et al., Dissolution of high burn-up spent nuclear fuel at high-pH. Radiochimica Acta, 2023. 111(11): p. 817-828.

Miksova, J., et al. Lessons Learned from Implementing Training and Mobility Programmes Within EC H2020 Projects EURAD and PREDIS. in ASME 2023 International Conference on Environmental Remediation and Radioactive Waste Management. 2023.

Van Winckel, S., et al., Assay data of spent nuclear fuel: the lab-work behind the numbers. Frontiers in Energy Research, 2023. 11.

El Jamal, G., et al., Study of Water Interaction with UO2 , U2O5 , and UO3 : Tracking the Unexpected Reduction of Uranium Cations and Characterization of Surface-Bound Hydroxyls. The Journal of Physical Chemistry C, 2023. 127.

El Jamal, G., et al., Monitoring the reduction of UO3 thin film by hydrogen atoms using valence-level spectroscopy: correlating the U5f1 signal to surface hydroxyls. Frontiers in Fuels, 2023. 1.

### NONCOWA

Mooren, E., Treatment of Liquid Radioactive Waste with Nanoparticles and Inorganic Polymers, European Commission, 2022, JRC132531.

Mooren, E., Incorporation of Cs, Sr, and Eu into copper slag inorganic polymers: matrix characteristics and leaching behaviour, Bonani, W., Van Winckel, S., Bulgheroni, A., Van Der Sande, J., Hertel, T., Beersaerts, G., Schreurs, S., Popa, K., Konings, R. and Schroeyers, W. editor(s), Presented in: 47th Scientific Basis for Nuclear Waste Management (SBNWM) Symposium, 2023, JRC133610.

## 05 Radioactivity in the Environment

The GERDA Collaboration, 'Search for Tri-nucleon decays of 76Ge in GERDA', European Physical Journal C, 2023, pp. 83:778, doi: s10052-023-11862-8.

The GERDA Collaboration, 'Final Results of GERDA on the Two-Neutrino Double-β Decay Half-Life of 76Ge', Phys. Rev Lett. 131, 2023, p. 142501, doi: 10.1103/PhysRevLett.131.142501.

The GERDA Collaboration, 'An improved limit on the neutrinoless double-electron capture of 36Ar with GERDA'. European Journal of Physics C , 2023.

The GERDA Collaboration, 'Light collection and veto modelling in GERDA Phase II', European Journal of Physics C, 2023, pp.83:319, https://doi.org/10.1140/epjc/s10052-023-11354-9.

Pommé, S., Veale, M., Pooley, D., Van Assche, F., Falksohn, F., Collins, S. 'Analysis of a neutrino-induced conversion electron spectrum of gadolinium'. Appl. Radiat. Isot. 197, 2023, p. 110828.

Yunoki, A., Miura, T., Yasushi, Sato, Y., Lee, P-F., Hult, M., Tzika, F., Lutter, G., Marissens, G., Lee, J., Lee, K.B., Nour, S., La Rosa, J., Saegusa, J., Soodprasert, T., Candra, H., Marsoem, P., Wurdiyanto, G., Hamamatsu, S., Hachinohe, M. 'APMP supplementary international comparison of activity measurement of Cs-134 and Cs-137 in brown rice', Metrologia Vol. 60 No. 1A, 2023,06007.

Pommé, S., Pelczar, K., 'Role of ambient humidity underestimated in research on correlation between radioactive decay rates and space weather', Sci. Rep. 12, 2022, p. 2527.

Pommé, S., Pelczar, K.,, I. Kajan, 'Air humidity and annual oscillations in 90Sr/90Y and 60Co decay rate measurements'. Sci. Rep. 12, 2022, p. 9535.

Pommé, S., 'Radionuclide metrology: confidence in radioactivity measurements'. J. Radional. Nucl. Chem. 331, 2022, pp. 4771-4798.

Pommé, S., Pelczar, K., 'Neutrino-induced decay: a critical review of the arguments'. Space Science Reviews 218, 2022, p. 64.

## 06 Nuclear Applications

### SPA, NuMaDIT, ULTIMATE

Popa, K., Vigier, J., Konings, R. and Freis, D., Ceramic compounds with high 241Am-content for radioisotope power systems, European Commission - Joint Research Centre, Karlsruhe, 2023, JRC132341.

Freis, D., Popa, K., Konings, R. and Vigier, J., Radioisotope Power Systems for Exploratory Space Missions, University of Pisa - MSc in Nuclear Engineering, Pisa, 2023, JRC133126.

Bonani, W., Boshoven, C., Cologna, M., Freis, D., Holzhäuser, M., Popa, K. and Vălu, S.O., PU-238-coupLed dynamic power system for SpAce exploRation and beyond (PULSAR), European Commission, Karlsruhe, 2023, JRC135081.

Bonani, W., Boshoven, C., Cologna, M., Freis, D., Holzhäuser, M., Popa, K. and Vălu, S.O., PU-238-coupLed dynamic power system for SpAce exploRation and beyond (PULSAR). Task 4.1 Part 1. Synthesis and characterisation of CeO2 pellets with representative microstructure, European Commission, Karlsruhe, 2023, JRC135081.

Zanini, A., et al, First Structured Uranium-Based Monoliths Produced via Vat Photopolymerization for Nuclear Applications. Advanced Funcional Materials, 2024, 2406916. https://doi.org/10.1002/adfm.202406916

Manaud, J., Corniani, E., Nakajo, A., Cambriani, A., Holzhaeuser, M., Cologna, M., Haehner, P., Vlahovic, L., Konings, R. and Freis, D., ULTIMATE Exploratory Research Project final report, European Commission, Karlsruhe, 2023, JRC135894.

Manaud, J., Nakajo, A., Corniani, E., Holzhaeuser, M., Cambriani, A., Cologna, M., Haehner, P., Vlahovic, L. and Konings, R., Spark plasma sintering and mechanical properties of tantalum carbonitrides Ta2CxNy., Open Ceramics, ISSN 2666-5395 (online), 18, 2024, p. 100598, JRC136388. https://doi.org/10.1016/j.oceram.2024.100598

Manaud, J., Cologna, M. and Vlahovic, L., Investigation of ultra-high temperature transition metals carbo-nitrides, Presented in: Ceramics in Europe 2022, 2022, JRC127754.

Manaud, J., Robba, D., Cambriani, A., Corniani, E., Nakajo, A., Haehner, P., Konings, R., Freis, D., Cologna, M. and Vlahovic, L., Ultimate - Investigation of Ultra-High Temperature Ceramics - ULTIMATE ER Project 2021 - 2023, Presented in: CASandER workshop, 2023, JRC135786.

Manaud, J., Robba, D., Cambriani, A., Corniani, E., Nakajo, A., Haehner, P., Konings, R., Freis, D., Cologna, M. and Vlahovic, L., Melting temperature and mechanical properties of tantalum carbonitrides Ta2CxNy, Presented in: Ultra-High Temperature Ceramics: Materials for Extreme Environment Applications VI, 2024, JRC137738.

Magill, J., et al., NUCLEONICA: a nuclear science portal. http://dx.doi.org/10.1051/ndata:07150, 2009. 1164.

## 07 Open Access & Nuclear Data

### ACTUSLAB

Autillo, M., et al., Temperature Dependence of 1H Paramagnetic Chemical Shifts in Actinide Complexes, Beyond Bleaney's Theory: The AnVIO22+–Dipicolinic Acid Complexes (An=Np, Pu) as an Example. Chemistry – A European Journal, 2021. 27(24): p. 7138-7153.

Chowdhury, S., et al., Laser Heating Study of the High-Temperature Interactions in Nanograined Uranium Carbides. Materials, 2021. 14(19): p. 5568.

Corradetti, S., et al., Effect of graphite and graphene oxide on thorium carbide microstructural and thermal properties. Scientific Reports, 2021. 11(1): p. 9058.

Düllmann, C.E., et al., Advancements in the fabrication and characterization of actinide targets for superheavy element production. Journal of Radioanalytical and Nuclear Chemistry, 2023. 332(5): p. 1505-1514.

Dutkiewicz, M.S., et al., A terminal neptunium(V)–mono(oxo) complex. Nature Chemistry, 2022. 14(3): p. 342-349.
Tereshina-Chitrova, E.A., et al., Role of disorder in magnetic and conducting properties of U–Mo and U–Mo–H thin films. Materials Chemistry and Physics, 2021. 260: p. 124069.

### EUFRAT

Noguere, G., et al., Time-of-flight measurements of MINERVE samples containing fission products and neutron absorbing isotopes. EPJ Web of Conf., 2023. 284: p. 01035.

Baják, P., et al., Natural Radioactivity in Drinking Water in the Surroundings of a Metamorphic Outcrop in Hungary: The Hydrogeological Answer to Practical Problems. Water, 2023. 15(9): p. 1637.

Tymiński, Z., et al., Underground radioactivity measurements of meteorites: Development of methods suitable to determine precise terrestrial age of recent falls. Applied Radiation and Isotopes, 2023. 195: p. 110733.

### INVISION

Haehner, P., Corniani, E. and Lorenzetti, L., On the generation of indentation stress−straincurves from spherical nanoindentation, Presented in 6th International Small Sample Test Techniques Conference, 2023, JRC134957.

Corniani, E., Haehner, P., Nakajo, A., Lorenzetti, L. and Martini, C., Miniaturised Membrane Bulge Test to Characterise Metal Foils down to 10 μm Thickness, Presented in: SSTT 2023, 6th International Small Sample Test Techniques Conference, 2023, JRC135140.

### GEMSTONE

Sibbens, G., et al., 'Target preparation for neutron-induced reaction experiments', EPJ Web of Conferences, Vol. 229, 2020, 04003.

Perkowski, J. et al., 'Multi-section ionization fission chamber for measurement of 239Pu(n,γ) reaction in fission tagging method', in preparation.

Tagliente et al., "92Zr(n, γ) and (n,tot) measurements at GELINA and n_TOF facilities", Physical Review C105 (2022) 025805, 10.1103/physrevc.105.025805.

Mucciola et al., "Evaluation of resonance parameters for neutron interactions with molybdenum" Nuclear Instruments and Methods B, Vol. 531, 2022, pp. 100 - 108.

Mucciola R., et al., 'Neutron capture and total cross-section measurements on 94,95,96Mo at n_TOF and GELINA", EPJ Web of Conferences, Vol. 284, 2023, 01031 10.1051/epjconf/202328401031.

Travar, M., Piau, V., Göök, A., Litaize, O., Nikolov, J., Oberstedt, A., Oberstedt, S., Enders, J., Peck, M., Geerts, W., Vidali, M., 'Experimental information on mass- and TKE dependence of the prompt fission gamma-ray multiplicity', Physics Letters B 817 (2021) 136293.

Piau, V., Litaize, O, Chebboubi, A., Oberstedt, S., Göök, A., Oberstedt, A., 'Neutron and gamma multiplicities calculated in the consistent framework of the Hauser-Feshbach Monte Carlo code FIFRELIN', Physics Letters B 837 (2023) 137648.


## 08 Knowledge Management & foresight


### KNOWMADIS

Tanarro Colodron, J., Simola, K., Cihlar, M., Liessens, A., Alvarez Sarandes Lavandera, R., Cambriani, A., Vanleeuw, D., Renda, G., Eulaerts, O., and Grabowska, M., European Commission, Joint Research Centre, Horizon scanning for nuclear safety and security yearly report 2022 – Creating an anticipatory capacity within the JRC, 2023: Publications Office of the European Union.

**PUBLIC ATTITUDES**

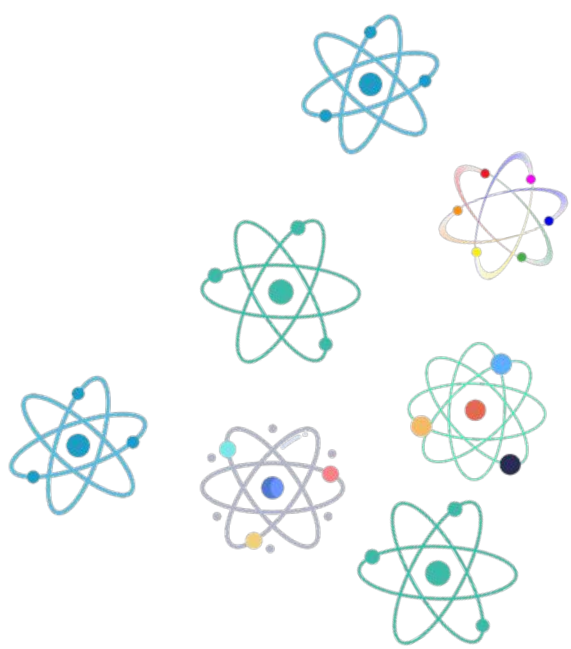
Public Attitudes toward Clean Energy 2023 - Nuclear (radiantenergygroup.com)

Citizens' attitudes towards nuclear energy and radioactive waste in particular:  Attitudes towards radioactive waste - July 2008 - - Eurobarometer survey (europa.eu)

A return to grace for nuclear power in European public opinion? Some elements of a rapid paradigm shift (robert-schuman.eu)

Levy, D. & Wallard, H. (2024). Les évolutions de l'opinion publique sur le nucléaire en France et en Europe. Annales des Mines - Responsabilité & environnement, 113, 79-82. https://doi.org/10.3917/re1.113.0079

Enquête d'opinion internationale sur le changement climatique - Obs'COP: Enquête d'opinion internationale sur le changement climatique - Obs'COP - data.gouv.fr



**Getting in touch with the EU**

**In person**

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

**On the phone or in writing**

Europe Direct is a service that answers your questions about the European Union. You can contact this service:
— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),
— at the following standard number: +32 22999696,
— via the following form: european-union.europa.eu/contact-eu/write-us_en.

**Finding information about the EU**

**Online**
Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

**EU publications**
You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

**EU law and related documents**
For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

**EU open data**
The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

# Science for policy

The Joint Research Centre (JRC) provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society

**EU Science Hub**
joint-research-centre.ec.europa.eu

Publications Office
of the European Union