European Commission

Science for Nuclear safety and security

JRC thematic report

Joint Research Centre (JRC)

The European Commission's science and knowledge service

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Joint Research Centre

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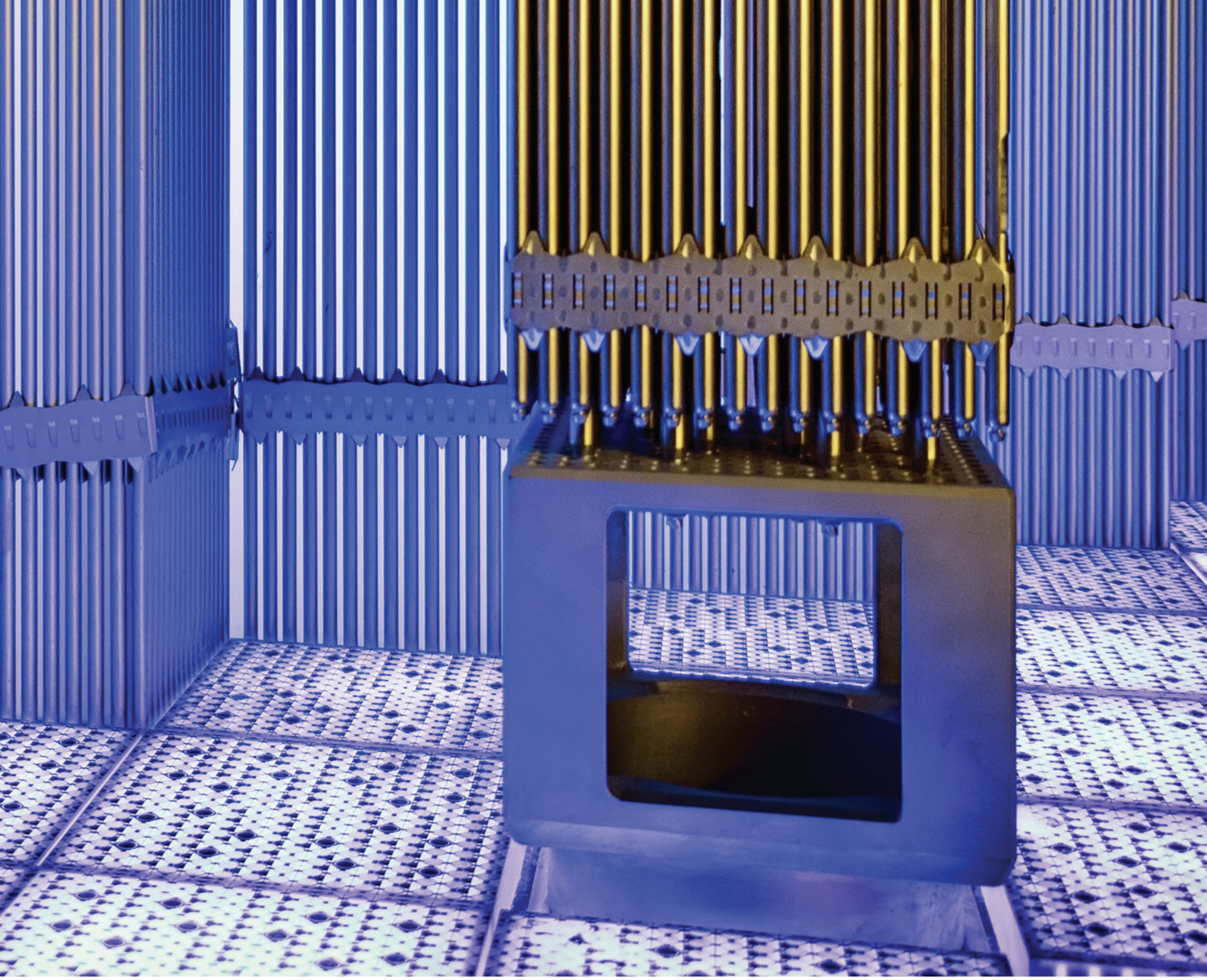
Foreword by Vladimír Šucha, JRC Director-General

In the European Union around 27% of electricity is produced by nuclear energy. Nuclear energy plays a fundamental role in the EU for it to meet its own targets to cut greenhouse gas emissions and to ensure its energy security. The choice to use nuclear power or not in the energy mix of each of the 28 EU Member States is a national decision and currently the situation differs significantly amongst them. Today, there are 14 countries in the EU operating over 130 reactors, two of which have clear phasing out policies, and four that are investing in new-builds.

Since 1957, the Euratom Treaty has foreseen a clear role for the EU in ensuring the safe and sustainable use of nuclear energy across Europe and helping the Member states meet the highest standards of safety, security and non-proliferation. Through the Joint Research Centre (JRC), the European Commission's in-house science service, the EU provides both direct research and policy support for nuclear safety and security issues, next to its scientific and technical expertise in other domains such as Economic and Monetary Union, public health and safety, or agriculture and global food security. It also tackles many societal challenges such as climate change, energy security or socio-economic inequality and therefore also strives to contribute to growth, jobs, innovation and a low-carbon economy. In addition, the JRC scientific support to EU policymaking benefits from its interdisciplinarity.

In the nuclear area it fulfils the research obligations of the Euratom Treaty. For over 50 years the JRC has been conducting direct research in the nuclear field and has been providing expertise to complement the training and education efforts of the Member States. JRC activities support the need for nuclear safety, security research and cross-cutting activities, in order to ensure that top-level competence and expertise for nuclear safety assessments are available in the EU.

The JRC, for example, carries out research in the field of nuclear fuel safety. This research area focuses on fuel behaviour under harsh reactor conditions. The JRC also



deals with pre-normative research on nuclear structural materials, resulting in codes and standards, novel test techniques and advanced inspection procedures. Another area of expertise is the development of nuclear reference materials, standards and measurements for benchmarks to control environmental radioactivity measurements and to check conformity assessments.

The JRC works very closely with the EU Member States, both to maximise synergies and to provide a knowledge pool for nuclear stakeholders.

In the context of its policy support role, the JRC contributes to the solutions for Europe's longer-term energy challenges, as well as helping to address citizens' concerns about current nuclear technology, in particular safety and security and waste management. For example, the JRC assists Member States in gathering feedback on operational experiences in the nuclear field and supports the exchange of radiological environmental monitoring. The JRC also has a significant policy support role in the EU, for instance by coordinating an EU action plan on chemical, biological, radiological and nuclear security, aiming to reduce the threat of such incidents, including terrorist acts.

The JRC has several strategic international agreements and cooperates with international organisations and partners such as the International Atomic Energy Agency (IAEA), the Nuclear Energy Agency of the Organisation of Economic Cooperation and Development (OECD/NEA), the US Department of Energy and third countries, such as Japan, Canada, China. In addition, the JRC is the Euratom implementing agent within the framework of the Generation IV International Forum.

This publication highlights the JRC activities in the nuclear research field and I hope that it will help the reader understand the need for solid science to meet global nuclear safety and security challenges and the JRC's role, which builds on our worldwide recognised expertise in this area.

Introduction

Ensuring nuclear safety and security is a priority for the EU. As the European Commission's in-house science service, the Joint Research Centre (JRC) supports the Commission in fulfilling the obligations originally set up by the Euratom (European Atomic Energy Community) Treaty in the areas of nuclear research, training and education, and radiation protection.

The JRC's nuclear research activities are defined in a Council Regulation on the research and training programme of the European Atomic Energy Community (2014-18), which complements the EU framework programme for research and innovation, Horizon 2020. The activities also fulfil the legal obligations under the Euratom Treaty (chapter III arts 36 and 39), and under several Euratom recommendations, decisions and directives.

The March 2011 Council as well as nuclear summits conclusions also emphasise the need to give priority to the highest standards for nuclear safety and security in the Union and internationally.

There are currently around 130 nuclear reactors in operation in 14 EU countries, which produce approximately one third of the European Union's electricity. The choice to use nuclear power or not in the energy mix of each of the 28 EU Member States is a national decision and currently the situation differs significantly among them. Some Member States have nuclear phase-out policies, whilst some others are opting for long-term operation and lifetime extension of their nuclear plants.

This report provides a comprehensive overview of the work of the JRC, the European Commission's in-house science service in the domain of nuclear safety and security. This research area encompasses the safety of nuclear reactors and the nuclear fuel itself, the safe operation of nuclear energy systems, as well as nuclear safeguards, non-proliferation and the fight against illicit activities involving nuclear and radiological material.

The description of the JRC's work is divided into five chapters, each chapter describing JRC research and relevant scientific outputs in the area, linked to their policy background and context. In addition, lists of facilities, partners and references as well as links to useful tools and websites are provided.

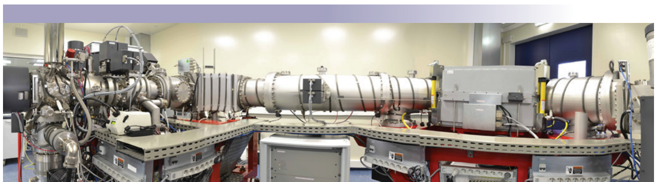
CHAPTER 1
Nuclear safety

Nuclear safety covers the whole life cycle of a nuclear installation. It includes: nuclear reactor safety, nuclear fuel safety, nuclear waste management and decommissioning and emergency preparedness, all activities that are covered by the JRC.

The JRC assists the Member States' nuclear safety authorities and their technical support organisations, as well as the European Commission services in this field, for example in the field of radiological information exchange.

The JRC also performs direct nuclear fuel safety research in its state-of-the-art experimental facilities. Its research focuses on safety limits of nuclear fuels and cycles under normal and accidental scenarios, and on the fuels' behaviour under harsh reactor conditions.

CHAPTER 2
Nuclear security



Nuclear security deals with the physical protection and control of nuclear materials. JRC research topics in this area include nuclear safeguards, Additional Protocol, open source information on nuclear non-proliferation, combating illicit trafficking of nuclear materials and nuclear forensic analysis.

The JRC provides scientific, technical and operational support to the Commission's Energy Directorate-General responsible for nuclear safeguards, the Directorate-General for Home Affairs and the Directorate-General for Development Cooperation under the chemical, biological, radiological and nuclear (CBRN) security action plan. It also cooperates with major partners in EU Member States and countries worldwide, as well as with the International Atomic Energy Agency (IAEA) in the areas of nuclear measurements, process monitoring, containment and surveillance and advanced safeguard approaches.

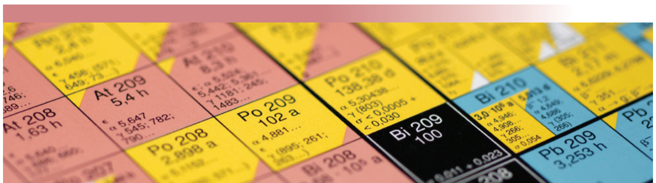
The JRC also contributes to the development and implementation of EU strategic trade controls, to the development of specific expertise in the forensic analysis of nuclear and radioactive materials, to the testing and standardisation of equipment and to the enhancement of border security and related training efforts for first frontline responders and national experts in the detection and identification of nuclear materials.

CHAPTER 3
Reference measurements, materials and standards

The EU helps to ensure that nuclear energy activities in all Member States are pursued and enforced with the highest standards of nuclear safety, security and non-proliferation. It is fundamental that these EU standards are also harmonised with global initiatives.

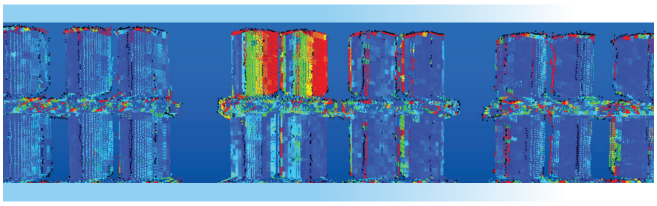
The JRC scientifically supports this harmonisation process and the enforcement of EU legislation by developing material and document standards. It is also a world-renowned and accredited provider of certified nuclear reference materials, nuclear reference measurements and determines benchmarks for the control of environmental radioactivity measurements and conformity assessments in order to establish confidence in measurement results of national safety and international safeguards authorities.

CHAPTER 4
Nuclear knowledge management, training and education



The Euratom Treaty clearly underlines the role of the European Commission as the responsible entity for facilitating nuclear research in Member States and for carrying out an EU research and training programme. This is crucial to maintain high levels of nuclear safety and security. To this end, the JRC monitors European human resources in the nuclear field, develops nuclear knowledge management and has established a comprehensive training programme on Nuclear Safety and Security.

CHAPTER 5
Fostering the innovation flow



The JRC pursues innovation through EU research programmes in the areas of nuclear materials for new reactor technologies, nuclear transmutation, nuclear safeguards and nuclear non-proliferation; and safety for innovative reactor designs.

The sustainable use of resources requires pushing the technological limits of materials and fuels. The JRC works on nuclear structural materials that can be used in harsh new reactor environments by performing pre-normative research and development (R&D), delivering qualified data into codes and standards, developing novel test techniques, and advanced inspection procedures, which are intended for use within Generation IV reactors, the new generation of reactors.

Long-lived radionuclides, which are a by-product of nuclear reaction, are still of major concern for nuclear waste management. Fundamental safety properties at different stages of irradiation are addressed by innovative JRC programmes for the transmutation of long-lived radionuclides.

R&D in nuclear safeguards and non-proliferation aims to prevent or detect the misuse of nuclear material. In order to tackle new security concerns associated with growing and increasingly advanced facilities, the JRC undertakes research and development in nuclear safeguards, non-proliferation and nuclear security with a view to develop high quality process monitoring, sealing and laser-based 3D verification techniques, and to carry out open-source media analyses.

The safety of innovative reactor designs is pivotal in view of their potential deployment in Europe. The JRC works in partnership with European and international organisations to develop safety assessment methodologies for innovative reactor designs, to define their criteria and to establish guidelines. It also investigates the application of innovative multi-physics computational approaches for safety analysis under simulated normal, transient and accidental operational modes.

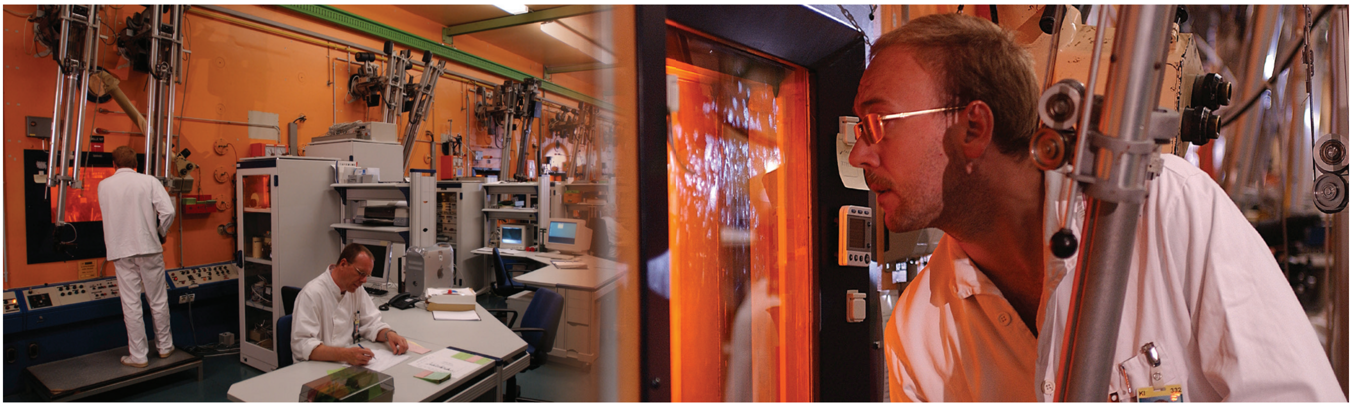
1 Nuclear safety

Nuclear safety covers the design, construction, operation and decommissioning of all nuclear installations (e.g. reprocessing plants, nuclear power plants and waste storage facilities) as well as fuel management. The JRC provides assistance and direct research in the fields of nuclear fuel safety, decommissioning, waste management radiological monitoring and emergency preparedness to both the Member States and the European Commission services. It assists EU countries directly via the European Clearinghouse on Nuclear Power Plants Operational Experience Feedback initiative, which analyses events in nuclear power plants worldwide. Its reactor safety research activities are focused on severe accident modelling, and on cooperation with international organisations such as the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development (OECD/NEA).

Within its experimental facilities, the JRC performs research to determine the safety limits of nuclear fuels and cycles under normal/off-normal operating conditions and severe accident scenarios. The main goals of the analyses are the determination and modelling of the evolution of the physical, chemical, and thermo-mechanical properties in the presence of increasing fission products and atomic displacement due to irradiation.

The JRC also works directly with industry in the field of decommissioning to improve governance and technology, since many nuclear installations in Europe will soon reach the end of their operational lifecycles.

Beyond EU borders, the JRC supports projects addressing nuclear safety in EU candidate countries (under the EU Instrument for Pre-Accession Assistance – IPA) and in other countries worldwide (under the EU Instrument for Nuclear Safety Cooperation – INSC). In addition, the JRC is closely cooperating with relevant national and international organisations to support the development and improvement of nuclear safety standards.



JRC hot cells facility for the study of the nuclear fuel safety.

JRC activities in this area provide scientific support to the following policy initiatives:

- Treaty establishing the European Atomic Energy Community (Euratom Treaty) – 1957
- Regulation 733/2008/EC of 15 July 2008 on the conditions governing imports of agricultural products originating in third countries following the accident at the Chernobyl nuclear power station
- Regulation 1048/2009/EC of 23 October 2009 on imports amending Regulation (EC) no 733/2008
- Regulation (Euratom) No 300/2007 of 19 February 2007 establishing an Instrument for Nuclear Safety Cooperation
- Regulation (Euratom) no 3954/87 of 22 December 1987 on maximum permitted levels of radioactive contamination of foodstuffs
- Regulation (EU) No 540/2010 of 16 June 2010 amending Council Regulation (EC) No 1085/2006 establishing an Instrument for Pre-Accession Assistance (IPA)
- Regulation (EC) No 1085/2006 of 17 July 2006 establishing an Instrument for Pre-Accession Assistance (IPA)
- Directive 2013/51/Euratom of 22 October 2013 laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption

- Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom and 2003/122/Euratom
- Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste
- Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumptionDirective 2009/71/Euratom of 25 June 2009 establishing a Community framework for the nuclear safety of nuclear installations
- Decision 87/600 of 14 December 1987 on Community arrangements for the early exchange of information in the event of a radiological emergency
- Recommendation 2000/473/Euratom of 8 June 2000 on the application of article 36 of the Euratom Treaty concerning the monitoring of the levels of radioactivity in the environment for the purpose of assessing the exposure of the population as a whole
- Conclusions of the European Council of 24 and 25 March 2011 on the mandate for the stress tests, EUCO 10/1/11
- Advanced fuel cycle options: Strategic Research and Innovation Agenda (SRIA) of the SNETP
- Geological disposal of High-Level Waste: Strategic Research Agenda of the IGD-TP (Implementing Geological Disposal of Radioactive Waste Technology Platform)

1.1 Reactor safety

Operational experience feedback (OEF) from the more than 400 operational nuclear reactors worldwide is important to improve nuclear safety. In order to maintain an effective feedback mechanism, a wide range of information needs to be accessed and processed. The European EU Clearinghouse initiative has therefore been set up, supporting the EU nuclear safety authorities, EU technical support organisations and international organisations, and the broader nuclear stakeholders community. The JRC operates its centralised office.

The experience gained has been key to the JRC's participation in a safety review of all EU nuclear power plants: a comprehensive and transparent risk assessment, known as the nuclear 'stress tests' organised by the European Commission and the European Nuclear Safety Regulators Group (ENSREG) in the aftermath of the Fukushima Daiichi accident in 2011. With the set-up of a project in 2012 on severe accident modelling and analyses for nuclear power plants, the JRC further reinforced its contribution to Europe's post-Fukushima nuclear safety efforts. The outcome will set the technical foundations for the review of EU legislation on nuclear safety.

The JRC has longstanding expertise in the field of severe accidents, including through its participation in the FP7 Severe Accident Research Network Of Excellence (SARNET), which mainly covers on-site phenomena (accident progression and source term evaluation) during the early and mid-term phase of a severe accident.

Beyond EU borders, the JRC supports projects addressing nuclear safety in EU candidate and other countries worldwide. In addition, the JRC is closely cooperating with relevant national and international organisations to support the development and improvement of nuclear safety standards.

Work in progress

The JRC is developing databases and organising training sessions to strengthen the feedback on operating experience of nuclear power plants in the EU. It is also conducting research on nuclear event evaluation methods and techniques, in support of long-term EU policy needs on operational feedback.

In addition, it collaborates with the Sustainable Nuclear Energy Technology Platform (SNETP) and provides support to European networks and associations related to severe accidents, such as SARNET and NUGENIA (Nuclear Generation II and III Association).

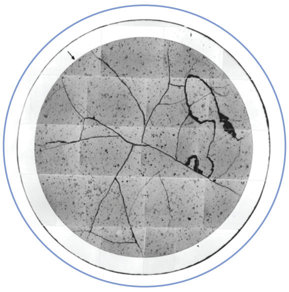
A new Euratom FP7 research project which focused on the Code for European Severe Accident Management (CESAM) was launched in 2013. It regroups 17 EU partners and India. The JRC has an active role in the project, as it contributes to modelling activities and leads the main part of the project, which focuses on power plant applications and severe accident management.

The ultimate aim is to provide recommendations and to contribute to the enhancement of severe accident management in European nuclear power plants, based on the understanding of severe accident phenomena and especially the ones relevant to Fukushima. This knowledge will be built on the further development of the ASTEC computer code (Accident Source Term Evaluation Code), the European reference computer code for the simulation of severe accidents in nuclear power plants (NPPs). ASTEC is jointly developed by the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) and the German Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), with the support of EU and non-EU partners.

Contribution to the understanding of severe accident phenomena, like the Fukushima accident.

1.2 Fuel safety

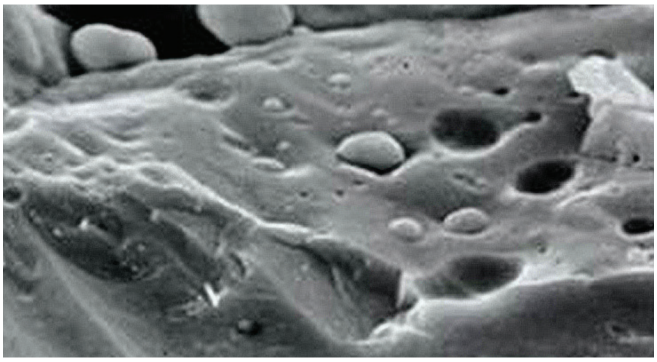
The safety of nuclear fuel is the basic safety requirement when producing nuclear energy. The fuel rods in the core of a reactor must retain all radionuclides while generating energy. The JRC uses experimental facilities and modelling codes to study the properties and behaviour of nuclear fuel, and to determine the safety limits under normal and off-normal operating conditions, including severe accident scenarios.



Optical microscope cross section (~10 mm diameter) of an irradiated commercial fuel rod.

The studies include fuel safety during irradiation in-pile and post-discharge from the nuclear reactor core. Safety issues relevant to conventional and advanced fuels and cycles in the EU, such as extended fuel operation (which permits higher fuel consumption, or 'burn-up'), fast reactor fuels (such as plutonium compounds), and closed cycle fuels incorporating minor actinides (neptunium, americium, curium) fall under the JRC research scope.

The JRC investigates physical, chemical and thermo-mechanical properties of nuclear fuels and materials. Fuel compounds (actinide oxides, carbides, nitrides and other special compositions) are prepared to characterise basic and safety-relevant properties, and to test specific aspects of their behaviour under irradiation conditions. Post-irradiation examination allows assessment of the response of fuel and cladding to the extreme solicitations experienced in the reactor. The effects on the properties of the fuel due to strong temperature and fission density gradients, combined with the intense irradiation damage and the accumulation of fission products, are also investigated.



High magnification morphology of fuel irradiated at high temperatures.

The JRC analyses cover morphology and structure, composition and phase distribution, heat and matter transport, mechanical and chemical interactions, and span from the atomic level to the macroscopic/operational one. They focus in particular on how the increasing presence of fission products and of displaced atoms in the crystalline lattice of the fuel causes macroscopic degradations of the lattice's mechanical properties (swelling, cracking), and its capacity to transport the heat generated by the nuclear fission process to the coolant.

TRANSURANUS is a computer programme which predicts the thermo-mechanical behaviour of fuel rods in nuclear reactors and during storage. It was developed by the JRC in 1982, and has since been used by safety authorities, industry, research centres and universities across the EU. The programme is part of a long tradition of high quality modelling at the JRC. To keep it at state-of-the-art level, it undergoes continuous development and updating, taking into account new understandings of physico-mechanisms determining the nuclear fuel properties, and new accurate sets of experimental data measuring those same properties. In many cases the experimental data are produced by the scientific facilities of the JRC.

In the context of recent EU funded programmes, the JRC developed detailed and physics-based models which have been fed into the TRANSURANUS code, along with new materials properties. For example, the fission gas behaviour model has been implemented and assessed during the most recent benchmark for fuel performance codes (Fuel Modelling at Extended Burnup - FUMEX-III) organised by the IAEA, while the model and material properties for actinide redistribution in mixed oxide fuels has been published and will be tested in the framework of the new benchmark organised by the Expert Group on Innovative Fuels from the OECD/NEA.

Work in progress

The JRC is studying emerging safety issues relevant for current and future trends in the EU. This involves examining mixed oxide (MOX) properties, fuel-cladding interactions, mechanisms for high burn-up structure (HBS) formation, behaviour of fuel during loss of coolant accidents (LOCA); exploring innovative fuels for nuclear light water reactors (LWRs) and small modular reactors (SMRs), and carrying out research into fuel systems for advanced reactors (plutonium compounds) and closed cycle fuels incorporating minor actinides (neptunium, americium, curium).

Fuel safety experiment at the JRC hot cells.

In addition, the JRC is preparing further severe accident studies on specific aspects of the Fukushima accident: extended loss of cooling, in-vessel materials interactions, off-vessel fuel-concrete interactions and spent fuel behaviour in cooling ponds.

The JRC also links its research to the main priorities of EU technology platforms and relevant networks (SNETP, NUGENIA, the European Sustainable Nuclear Industrial Initiative – ESNII, and the European Energy Research Alliance – EERA).

1.3 Nuclear waste management and decommissioning

The Euratom Treaty and the Waste Directive (2011/70/EURATOM) establish the basis for responsible and safe management of spent fuel and radioactive waste in the EU, building on a series of internationally accepted principles, such as the protection of present and future generations. The goal of radioactive waste management is therefore disposal under robust safety conditions. The JRC contributes directly to the implementation of the Waste Directive by supporting the European Nuclear Energy Forum (ENEF) in guiding the Member States.

Photoemission spectrometer to study surface phenomena relevant for spent fuel corrosion processes.

A key challenge is the disposal of high-level waste in deep geological repositories. The amount and type of such waste depends on the national nuclear programme and the fuel cycle option used. Nowadays, the two main management options for spent fuel are reprocessing or direct disposal. Through research the JRC supports Member States on the long-term safety of disposed high-level waste and spent fuel. Large amounts of waste will be generated in the coming decades because a significant number of nuclear facilities will reach the end of their useful life.

In the context of the nuclear waste and decommissioning, the European Commission is committed to protecting citizens and the environment from radiological hazards associated with its activities. To this end in 1999, following a Communication to the European Parliament and the Council of the EU, a Decommissioning & Waste Management Programme was established for all its nuclear sites. To ensure the efficient execution of the Programme, the JRC is supported by a group of independent and impartial nuclear experts. The JRC Decommissioning & Waste Management Programme includes the decommissioning and dismantling of its obsolete nuclear installations, the management of existing radioactive waste and nuclear materials (so-called 'historical liabilities'), the decommissioning of operational nuclear installations and of the waste management infrastructure (so-called 'future liabilities').

Work in progress

The JRC is providing technical support to the Commission's Directorate-General for Energy for the assessment of the implementation at national level of the Waste Directive.

It is also studying the safety aspects and criteria of spent fuel during extended storage, subsequent handling and transportation. The JRC is additionally involved in several relevant R&D programmes, to improve the safety case, including operational safety during industrial implementation of both waste management options (i.e. partitioning and transmutation, and final disposal processes).

The JRC will furthermore create a decommissioning 'reference centre' in view of harmonising and standardising the methods for clearance measurements in the EU.

Nuclear fuel rods used in reactors are typically hollow metallic tubes of 4 m long and a diameter of about 10 mm, containing a stack of ceramic pellets made up of uranium or uranium-plutonium dioxide.

Transporting them safely is key to the back-end of the nuclear fuel cycle. To optimise the analysis of hypothetical accidents, the authorities demand that some know-ledge gaps (and the related experimental data) are filled.

One of these gaps is how much fuel would be released from a spent fuel rod in case of an accident causing mechanical failure. The JRC investigated the resistance of spent fuel rods against severe impact: «crash tests» were performed on spent fuel rods from different reactor types and with different characteristics.

The JRC, in collaboration with AREVA and the Gesellschaft für Nuklear-Service (GNS), characterised the fracturing behaviour and the fuel release. The conclusions were that under these impact conditions only a relatively limited amount of fuel is released from the rod. These types of studies are now widened to include the possible effects of extended storage time on the impact resistance of the spent fuel rods.

1.4 Emergency preparedness

Lessons learnt after the Fukushima accident highlight the importance of well-defined and established emergency response procedures involving all actors (operational, technical, regulatory and legal entities).

During the early phase of a large-scale accident with the release of radioactive material, it is not only essential to notify competent authorities as early and efficiently as possible, but also to rapidly exchange relevant radiological information. Only timely information on the (likely) contaminated area can lead to sound and internationally coordinated actions to protect the affected population.

Under the Euratom Treaty, EU countries are obliged to continuously monitor radioactivity in the air, water and soil, and report it to the European Commission. During the early phase of an accident it is not only important to exchange monitoring information, but also to use it for estimating the dispersion of radioactivity in the environment. A concept for an operational system that links the European information systems (see further) with predictive radio-ecological models for the various environmental areas is being developed by several national European research institutes. Dedicated efforts will thus be needed to integrate measurements and models (for example to identify areas likely to be contaminated to an extent that would require appropriate but potentially costly countermeasures like the removal of associated agricultural products from the market).

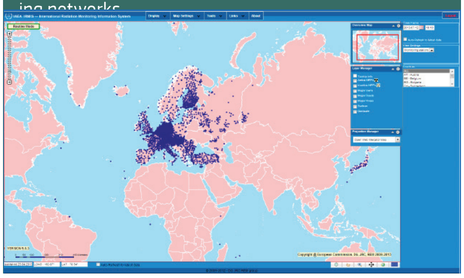
Today, the EU exchanges this kind of information through two main information systems: EURDEP (the European Radiological Data Exchange Platform) and ECURIE (European Community Urgent Radiological Information Exchange), both conceived, developed, tested and implemented by the JRC, assisting therefore both Member States and candidate countries in meeting their legal reporting obligations. At the same time, international data standards and protocols with the IAEA have been developed and implemented to keep these information systems compatible with the EU countries' international obligations.

The JRC is also responsible for the development, testing and implementation of the ECURIE-related software. WebECURIE uses web technology and therefore only internet access is required for the national contact points to operate it. The emergency information is handled in a bulletin board style, which the Member State authorities really appreciate as it allows them to handle the large amount of information in a very orderly manner in case of an exercise or accident.

The software has been officially tested for the first time during the IAEA-organised international emergency response exercise (ConvEx3) in November 2013 where it was found to be operating according to expectations.

When collecting radiological data from different national sources, it is most important to understand how the monitoring in the Member States is done (sampling methods and procedures, measuring and reporting techniques or the design of the networks). The JRC carried out scientific analyses to formulate recommendations on how this can be harmonised at international level.

The European Radiological Data Exchange Platform (EURDEP) facilitates the transmission of large datasets from radioactivity environmental monitoring networks



EURDEP web interface showing the on-line gamma dose-rate monitoring stations in Europe.

The JRC is also establishing the Reference Centre for Radioactivity Measurements in the Environment and Food to evaluate

It continuously makes data available from 39 organisations in 37 European countries, from about 4400 automatic gamma dose-rate stations on an hourly basis and some 100 air concentration monitoring stations on a daily basis during an emergency, as well as under normal conditions.

On a global level, the JRC assists the IAEA in developing its International Radiation Monitoring Information System (IRMIS). In this concept, EURDEP will continue to act as the European real-time monitoring network and the European Commission (through the JRC and the Directorate-General for Energy) will remain the European contact point for IRMIS. In addition, the JRC will provide technical assistance to test the initial data exchange with the IAEA member states outside Europe. The EURDEP concept, as a regional data exchange system, will also serve as a prototype for setting up regional networks in other parts of the world. In this context, the JRC will start a feasibility study in South-East Asia in 2014, in collaboration with the IAEA.

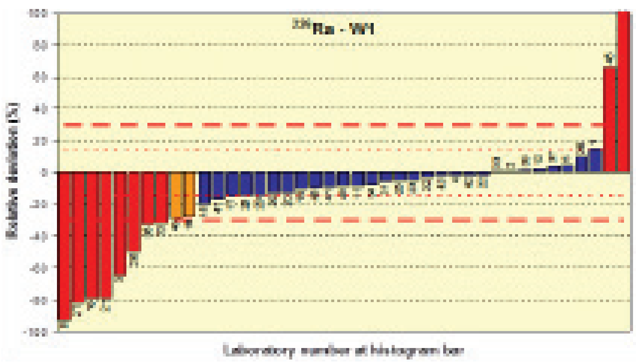
the performance of quick measurement methods, and to provide science-based advice to policy-makers and responsible laboratories alike.

The JRC organises regular inter-laboratory comparisons among the monitoring laboratories of Member States to assess the comparability of the monitoring data. These provide the laboratories with a means of benchmarking their performance and improving their measurement capabilities.

Work in progress

The JRC is adapting the current information exchange systems to allow access through social media and to involve countries outside of Europe. At the same time it is investigating the most efficient way to transfer the content.

It is also analysing existing environmental radioactivity networks, focusing on their design and how to improve the harmonisation between their results. In this context, the JRC is further exploring how existing radio-ecological models might make better use of raw data, providing prognosis of radioactivity dispersion in the environment.



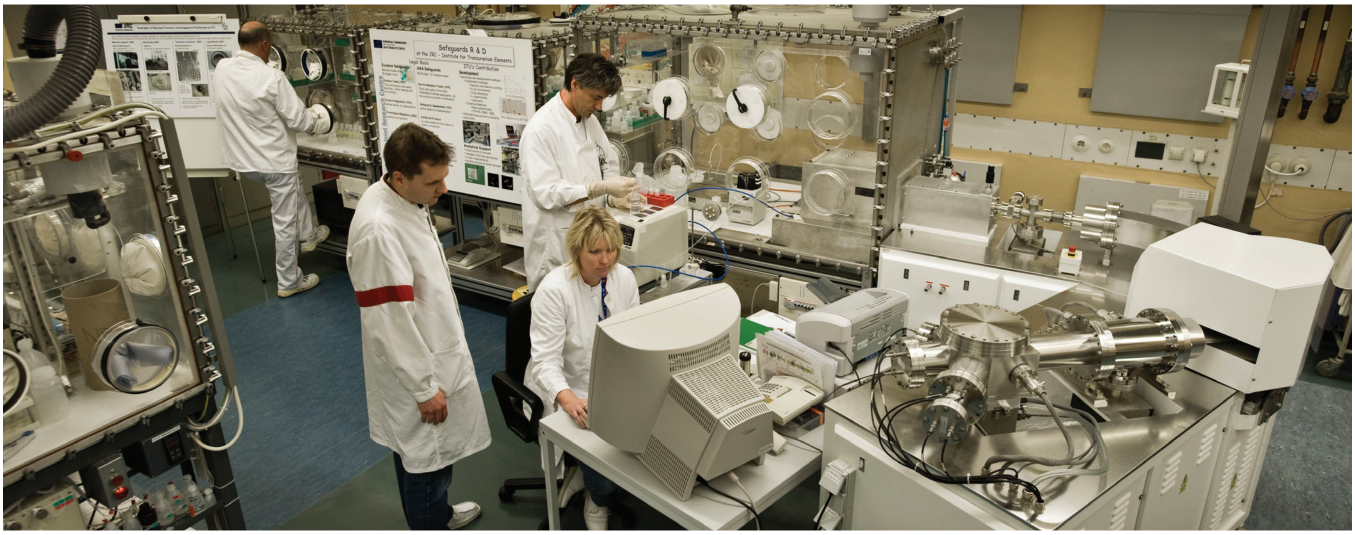
Results of the monitoring laboratories for the determination of ^{228}Ra in mineral water.

In addition, the JRC is preparing an inventory of methods used to monitor radioactivity in food and of the corresponding regulatory framework in the Member States and at community level. In a second phase, recommendations to improve harmonisation between Member States will be provided.

2 Nuclear security

The 1957 Euratom Treaty was the first cornerstone of EU engagement in nuclear safety and security. It introduced a strict system of safeguards to ensure that nuclear materials are only used for declared, peaceful purposes. The EU has exclusive powers in this domain, which it exercises with the aid of a team of inspectors who enforce the safeguards throughout the EU. Within its framework and with the framework of the European Safeguards Research and Development Association (ESARDA), the JRC has been providing scientific, technical and operational support and cooperates with major partners in the EU.

At international level, the European Commission provides scientific support and technical developments to the International Atomic Energy Agency (IAEA). The JRC supports the IAEA in the areas of nuclear measurements, process monitoring, containment and surveillance and advanced safeguards approaches. This includes the development of tools to support the identification of illicit procurement activities, as well as the development and implementation of EU strategic export controls through technical assessments and capacity building programmes.



JRC nuclear safeguards and forensic laboratory with mass spectrometry instrumentation.

The JRC co-organised the EU high-level event on "international cooperation to enhance a worldwide nuclear security culture" in the run-up to the 2014 nuclear security summit in Amsterdam. More than 100 participants from around 40 countries – including Member States, the United States, Japan, the Republic of Korea and Canada – and international organisations participated in the event. The participants identified three main enablers for a strengthened nuclear security culture: people and culture; legal frame and best practice; and knowledge and technological advancement. Co-operation at all levels and an integrated, holistic approach were singled out as the main drivers towards enhanced nuclear security.

In the area of combating illicit trafficking of nuclear and radiological materials, significant progress has been made in recent years with an EU action plan on chemical, biological, radiological and nuclear (CBRN) security. The CBRN action plan also addresses the need to reduce the threats of this type of incident, including terrorist acts.

The EU has developed particular expertise in the forensic analysis of nuclear and radioactive materials and in the testing and standardisation of detection equipment. Training programmes have been developed for first frontline responders and national experts in the detection and identification of nuclear materials, and the enhancement of border security and related training efforts. These are internationally coordinated, with the US and the IAEA, through the Border Monitoring Working Group (BMWG). Progress in nuclear forensics through the International Technical Working Group on Nuclear Forensics (ITWG) also merits special mention.

JRC activities in this area provide scientific support to the following policy initiatives:

- Treaty establishing the European Atomic Energy Community (Euratom Treaty) – 1957
- The International Treaty on the Non-Proliferation of Nuclear Weapons of 22 April 1970 (INFCIRC/140) and associated Additional Protocol
- United National Security Council Resolution 1540(2004) – All states shall act to prevent proliferation of mass destruction weapons

- The European Union Counter-Terrorism Strategy (14469/4/05 REV4), 30 November 2005
- A secure Europe in a Better World – European Security Strategy adopted by the European Council on 12 December 2003
- Fight against the proliferation of weapons of mass destruction - EU strategy against proliferation of Weapons of Mass Destruction (15708/03), adopted by the Council of the European Union on 10 December 2003
- Regulation No 428/2009 of 5 May 2009 setting up a Community regime for the control of exports, transfer, brokering and transit of dual-use items (Recast)
- Regulation No 1717/2006 of 15 November 2006 establishing an Instrument for Stability
- Regulation No 3227/76 of 19 October 1976 concerning the application of the provisions on Euratom safeguards
- Communication from the Commission of 26 March 2009 on nuclear non-proliferation, COM/2009/0143
- Council conclusions on strengthening chemical, biological, radiological and nuclear (CBRN) security in the European Union - an EU CBRN Action Plan, 15505/1/09 Rev.1
- Council Conclusions and new lines for action by the European Union in combating the proliferation of weapons of mass destruction and their delivery systems, 17172/08

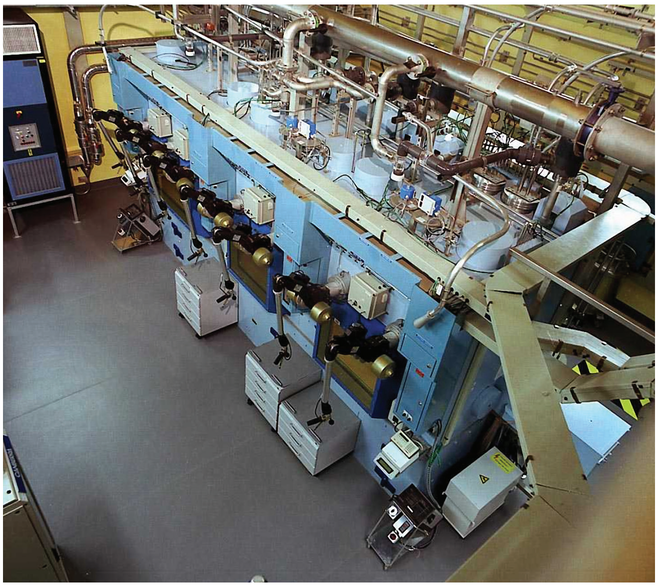
2.1 Safeguards

Under the Euratom Treaty, the European Commission has the duty to verify that nuclear material is only used for declared purposes. The aim of the EU regional safeguards system is to deter the diversion of nuclear material from peaceful use by maximising the chance of early detection.

The JRC supports DG Energy, whose mission is to ensure that nuclear material within the EU is not diverted from its intended use, and that the safeguarding obligations that have been agreed with third parties are complied with. At an international level, the JRC provides the International Atomic Energy Agency (IAEA) with instruments, tools and methodologies for the control of nuclear materials and facilities in order to avoid proliferation or diversion.

In the EU, the nuclear fuel cycle is present in all areas, from uranium enrichment, to fuel production, power reactors, spent fuel reprocessing and final disposal, which makes the full effective and efficient implementation of the safeguards and security requirements a challenging task. Technological advances are needed and the large flows of nuclear materials call for continuous improvements.

JRC contributions to R&D have been fundamental to assuring better safeguards. The JRC provides for example technologies to safeguarding authorities in various fuel cycle domains such as enrichment, fuel fabrication, reprocessing facilities and final disposal.



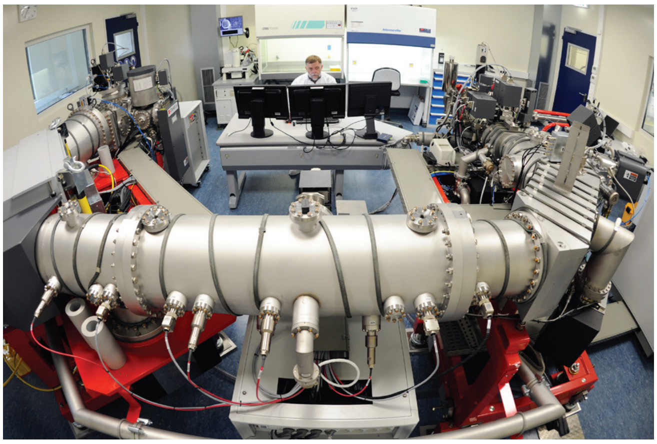
Euratom on-site laboratory at the reprocessing plant in La Hague (France) operated by the JRC.

It also operates the analytical on-site laboratories at the two largest European reprocessing plants in the nuclear sites of Sellafield (UK) and La Hague (France) whose throughput represents 80% of the world's reprocessed spent nuclear fuel. JRC experts are present on-site for more than 40 weeks per year, carrying out on average 800 spent fuel analyses. The JRC sample investigations, which are for nuclear accountancy, allow Euratom inspectors to check the fissile material chain and inventory of the nuclear facilities, thereby ensuring that nuclear material is not diverted from its intended use.

Euratom safeguards are strongly interlinked with those of the Member States and international organisations, such as the IAEA. Key partnerships have also been developed with the US Department of Energy (R&D agreement on nuclear safeguards and security), Russia, Japan and China.

Safeguards need to be taken into account from the early design phases when building new facilities, this is the so-called 'safeguards-by-design' concept. Together with the Directorate-General for Energy and the IAEA, the JRC supports these efforts and contributes to the activities of the proliferation resistance and physical protection (PRPP) working group of the Generation IV International Forum (GIF).

The JRC's nuclear safeguards activities have been significantly improved by the opening of the Large Geometry Secondary Ion Mass Spectrometry (LG-SIMS), a new analytical laboratory for nuclear micro-particles analysis. With this state-of-the-art facility, JRC scientists can detect – within a few hours – the existence of nuclear particles in samples taken during safeguards inspections and determine their enrichment level. This allows international safeguards authorities to verify the absence of undeclared nuclear activities. The newly-applied technique has been evaluated and developed by JRC scientists in close collaboration with leading equipment manufacturers in the field; this innovation will both enhance and speed up the nuclear verification process.



Large Geometry – Secondary Ion Mass Spectrometer for the analysis of particles which contain nuclear materials. Inaugurated in 2012, the joint JRC and DG ENER project verifies ^{235}U enrichments in declared facilities and supports the IAEA for the detection of undeclared nuclear activities.

Work in progress

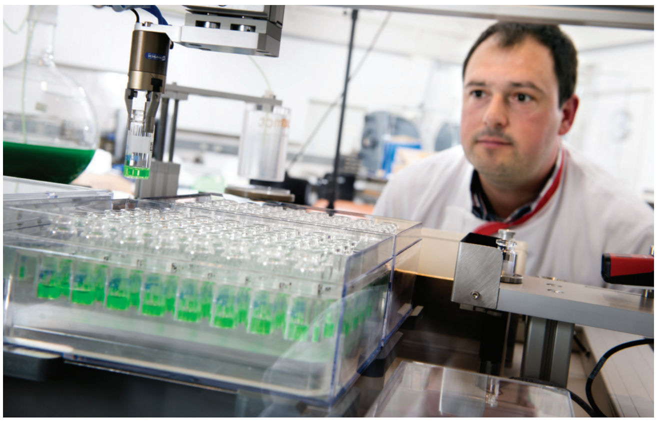
The JRC is carrying out R&D on material signatures for the improved characterisation of inspection samples (nuclear forensics for safeguards purposes). It is also improving the accuracy of measurement systems to allow more robust safeguards conclusions.

Work in progress is also related to advanced non-destructive assay systems (automated modelling for numerical calibration, alternative neutron detectors, cylinder verification at centrifuge enrichment plants, spent fuel assay) and the identification and design information verification (DIV) through 3D laser applications and innovative seals.

In addition, the JRC is studying the potential of open source information including satellite imagery and trade data, and it is developing new methodological approaches to safeguards and proliferation resistance evaluation methodologies.

The JRC is also performing R&D to support the new IAEA state evaluation concept, in particular in the area of acquisition paths analysis. It is continuing its work on safeguards-by-design, and together with the Commission's Directorate-General for Energy, it is supporting the facility specific guidelines that are being prepared under the IAEA auspices.

2.2 Non-proliferation



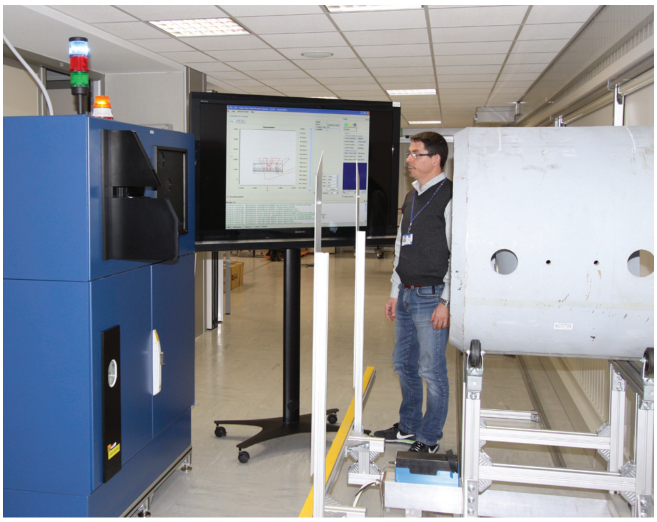
JRC provides reference materials for nuclear safeguards verification.

Nuclear proliferation remains a major concern for global stability and peace. Despite clear and binding legislation (such as the Non Proliferation Treaty), the IAEA's onsite inspections and state-analysis capabilities, and the United Nations Security Council resolutions and sanctions, there are a number of countries that are still of significant concern. While some of these have signed agreements with the IAEA, others refuse to collaborate with the international community. It is crucial to be able to determine the nature of the possible nuclear proliferation threat. In addition, the threat of non-state actors accessing nuclear-sensitive technology and nuclear weapons should also be considered.

The JRC develops new tools, approaches and analysis capabilities in this field. Its work can be divided in three main areas: verifying the declarations of nuclear materials operators and the absence of undeclared activities, determining indicators to detect clandestine activities and developing technologies for the verification of the effective disarmament of nuclear weapons.

For checking abnormal and clandestine activities or facilities (or the declared absence thereof) the JRC develops advanced, innovative techniques and in-field deployable tools (using self-localisation, ambient intelligence, augmented reality tools) and investigative radio-analytical methodologies for the IAEA to evaluate material properties against what has been declared.

It also carries out highly sensitive trace and particle analysis both through environmental monitoring and inside the facilities.



JRC Design Information Verification (DIV) laboratory for safeguards purposes.

The JRC also aims at developing indicators which can point to the build-up of possible clandestine activities and thus determine proliferation threats by country, focusing on the technology, know-how and components required for such activities and their trading. This is done for instance through research on sensitive dual-use technologies and goods subject to strategic export control and through the support to export control actors, such as industry and technology providers, licensing authorities, enforcement and jurisdiction institutions. The JRC also provides technical support and capacity building to the Commission and Member States.

Finally, the JRC supports the development of independent verification technologies and control of arms dismantlement.

After clandestine, undeclared nuclear programmes came to light, the International Atomic Energy Agency (IAEA) sought to use information sources in addition to state-declared information to derive indicators of possible undeclared, safeguards-relevant activities. In support to the IAEA, the JRC has surveyed and catalogued open sources on import and export, customs trade data and developed tools for their use in safeguards. Tests on the use of this data by the IAEA suggest safeguards relevance along a number of lines, including improving the understanding of a state's nuclear programme and supporting the verification of nuclear related exports worldwide.

The JRC's work on trade analysis contributed to findings on procurement activities of proliferation concern reported by the IAEA. Since then the IAEA has used trade data sources and analysis techniques developed by the JRC on a regular basis. The IAEA stated that the new approach developed by the JRC 'provided very useful results and will be instrumental to the consolidation of information driven safeguards'.

Work in progress

The JRC is further defining, qualifying and quantifying innovative indicators, focusing on tools for integrated nuclear non-proliferation analysis, using multiple source information based on in-field data (where available); on IAEA reports; open source information and daily news; independent data gathering from specialised databases (e.g. trade); and on advanced analyses of technical capabilities, environmental sampling and remote observation.

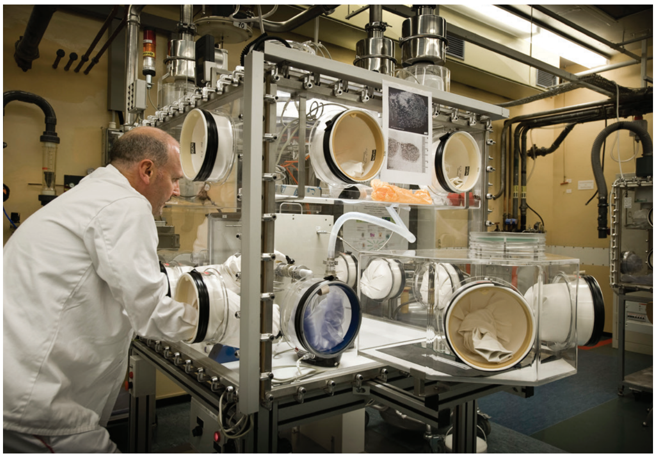
In addition, it supports the efforts against the illicit trade of dual-use goods by contributing to the definition of guidelines for harmonised trade controls; by performing research and technical studies on dual-use technologies; supporting EU services in amending dual-use control lists; delivering capacity building and training for authorities in the EU and candidate countries and by performing enhanced internal compliance programmes for research and industry.

2.3 R&D activities to combat illicit trafficking

Illicit trafficking of nuclear and other radioactive material remains an issue of concern due to radiological hazards linked to proliferation and the threat of nuclear terrorism.

Since 1993 more than 2 300 incidents were registered in the IAEA's Incident and Trafficking Database, more than 200 of which involved nuclear material. Illicit nuclear trafficking begs the questions why, how and where the material has spun out of regulatory control, what the geographical and historical origin is, and what the intended use could be.

Nuclear security measures aim to address these concerns by enhancing prevention, detection and response mechanisms.



JRC nuclear forensics laboratory for fingerprint and DNA analysis.

With its long-standing experience in handling and analysing nuclear material, its high-level expertise and specialised facilities, the JRC is perfectly equipped to develop technical solutions to the nuclear security challenges. Of course, the JRC also cooperates with a wide range of other key players in this area.

The JRC's R&D in combatting illicit trafficking focuses on nuclear detection technologies, testing and standardisation of equipment, responses to illicit trafficking incidents and nuclear forensic science. The JRC for example develops strategies and tests technologies for advanced radiation detection systems and for alarm adjudication, in particular with a view to 'innocent' alarms. In response to illicit trafficking, it conceived a model that could foster the implementation of national response plans. It also ensures that law enforcement needs are included in responses to radiological and nuclear incidents. In the area of nuclear forensics the JRC studies 'nuclear signatures' (which provide hints on the history and origin of the material), develops analytical and interpretational methods supporting the attribution of nuclear material of unknown origin, and performs analyses of seized nuclear material in support of EU Member States, international organisations and countries outside the EU.

Work in progress

The JRC activities in the area of nuclear security are intertwined with strategic collaborations with the IAEA and the US Department of Energy (DOE). The work currently focuses on developing advanced detection systems for neutron and gamma radiation, on strengthening the JRC's leading role in nuclear forensics and improving the nuclear forensic toolset.

2.4 Chemical, biological, radiological and nuclear hazards mitigation

In an international security context, preventing and mitigating chemical, biological, radiological and nuclear (CBRN) hazards has become crucial. Through the EU CBRN action plan, the EU significantly contributes to the international efforts to mitigate the associated threats and risks.

The role of the JRC here lies in conducting radiological and nuclear research, mainly in the areas of detection technologies, forensics, response and training.

The EU CBRN action plan is implemented through the Prevention of and Fight against Crime work programmes of the Commission's Directorate-General for Home Affairs (DG HOME). As a member of the CBRN advisory group, the JRC gives technical support to the implementation of the plan which is guided by consultation with national authorities and other relevant stakeholders such as the IAEA, Interpol and Europol.

In this context, the JRC manages EUSECTRA, a security training centre, and is responsible for the Illicit Trafficking Radiation Assessment Programme (ITRAP+10). The JRC is also working on a CBRN glossary, contributing to the IAEA illicit trafficking database and supporting its expertise in nuclear forensics. In addition, it offers virtual reality trainings and studies performance of portal monitoring under environmental conditions.

Illicit trafficking radiation assessment programme (ITRAP) facility at the JRC.

The JRC also supports the technical implementation of the EU Centres of Excellence on Chemical, Biological, Radiological and Nuclear Risk Mitigation (CBRN CoE Initiative) outside the EU. This initiative aims to implement a coordinated strategy for mitigation and preparedness against risks related to CBRN material at the international, regional and national levels and to boost cooperation.

The origin of the risk can be criminal (proliferation, theft, sabotage and illicit trafficking), accidental (industrial catastrophes, in particular chemical or nuclear, waste treatment and transport) or natural (mainly pandemics). There are currently more than 40 non-EU countries involved. Working in close collaboration with the Directorate-General for Development and Cooperation, the JRC has been instrumental in the setting up and opening of the CBRN regional secretariat, providing technical support such as evaluation and quality control, needs assessment and knowledge management.

JRC support includes developing CBRN guidelines and National Action Plans, and carrying out needs assessments; monitoring and evaluating sustainability aspects of projects and undertaking quality control; sharing information, disseminating best practices; and maintaining the CoE private 'Coordination and Communication' portal developed by the JRC.

EUSECTRA outdoor lab with portal monitors which simulates border controls.

The JRC has developed a method for rapid and accurate age dating of uranium samples. Nuclear forensic science makes use of measurable material parameters that provide hints on origin, age and intended use of the material. Using the radioactive decay of nuclear material allows determining the date of the last chemical separation, referred to as the 'age' of the material. Research has resulted in new signatures and improved analytical methods. Determining the production date of nuclear material is particularly important for investigating authorities.

In addition, the JRC produced the first certified reference material for uranium's production date and carried out an inter-laboratory comparison exercise.

Work in progress

The JRC has been tasked by the Commission's Directorate-General for Home Affairs to extend the ITRAP+10 project to include additional equipment and pave the way towards further equipment standardisation together with EU Member State laboratories. The JRC also runs a project on the inter-comparison of short range dispersion modelling for nuclear security events (such as terrorist attacks) with the EU Member States and proposes a benchmark study to analyse the use of these models in decision support systems for nuclear emergencies.

On behalf of the Commission's Directorate-General for Development and Cooperation, the JRC also assures the international coordination of nuclear security outreach projects (including security of radioactive sources, detection of and response to illicit trafficking and export control) and helps the countries benefiting from support under the Instrument for Stability in the analysis of their needs, the prioritisation of projects, the monitoring of ongoing work and the evaluation of the impact of executed projects.

3 Reference measurements, materials and standards

EU instruments, in particular standards and directives, must be in line with global initiatives, such as those coming from international conventions and nuclear safety standards, including the IAEA and OECD/NEA. The JRC supports this harmonisation process by developing reference materials, measurements and standards.

Not only for nuclear safety legislation is there a growing demand for harmonised approaches, but also for modelling tools used for safety assessments of nuclear installations. Despite enormous progress, modern safety evaluations with reduced error margins still ask for substantial additional research efforts both on nuclear and materials properties.

The JRC is a world-renowned and accredited provider of nuclear reference materials and measurements, which are important tools for the enforcement and monitoring of EU legislation, such as the Euratom Treaty. As the guardian of the European treaties, the Commission watches over the effective regional nuclear safeguards, by implementing inspections, reporting and providing technical and scientific support to its Member States in close partnership with the IAEA.

The JRC supports these activities by developing and providing nuclear reference materials and standards, which are used as benchmarks for control measurements and conformity assessments, so that safety and safeguards authorities and nuclear laboratories can demonstrate that their measurement results are reliable, traceable and globally comparable. The JRC also performs reference measurements that are used for safety and security assessments and for implementing standards.

JRC activities in this area provide scientific support to the following policy initiatives:

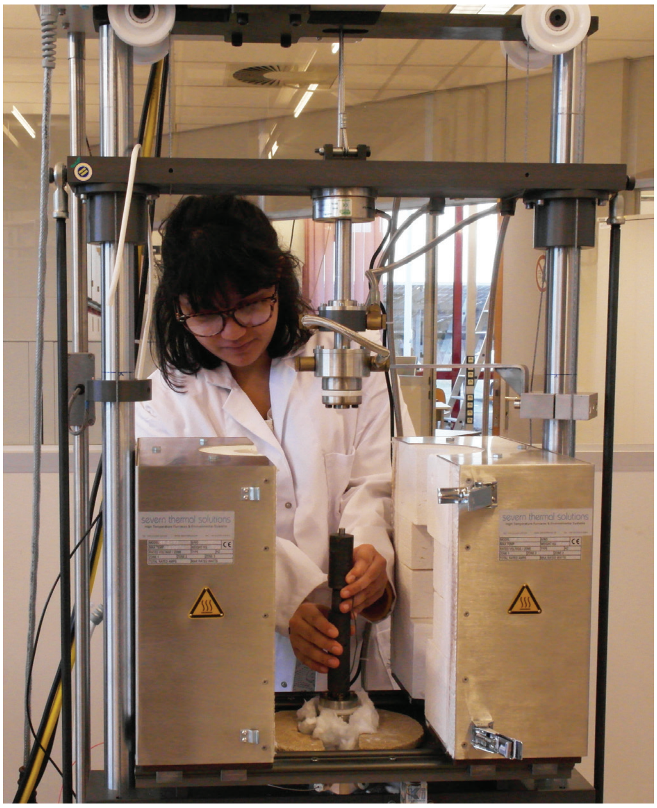
- Treaty establishing the European Atomic Energy Community (Euratom Treaty) – 1957
- Regulation No 1025/2012 of 25 October 2012 on European Standardisation
- Regulation (Euratom) No 302/2005 of 8 February 2005 on the application of Euratom safeguards - Council/Commission statement
- Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste
- Directive 2009/71/Euratom of 25 June 2009 establishing a Community framework for the nuclear safety of nuclear installations
- Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom and 2003/122/ Euratom
- Council Decisions 2010/212/CFSP of 29 March 2010 to strengthen the Non Proliferation Treaty as the cornerstone of the international nuclear non-proliferation regime
- Council Decision 2012/212/CFSP of 29 March 2010 relating to the position of the European Union for the 2010 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons
- Communication from the Commission of 1 June 2011 - A strategic vision for European standards: Moving forward to enhance and accelerate the sustainable growth of the European economy by 2020, COM(2011)311
- Communication from the Commission of 28 October 2010 - An Integrated Industrial Policy for the Globalisation Era Putting Competitiveness and Sustainability at Centre Stage, COM(2010)614
- Council conclusion from 24 and 25 March 2011 on the implementation and continuous improvement of highest standards for nuclear safety
- European Council conclusions of 25 September 2008 on standardisation and innovation
- Commission Staff Working Paper, Materials Roadmap Enabling Low Carbon Energy Technologies of 13 December 2011, SEC(2011)1609 final
- Commission Staff Working Paper accompanying the Communication (COM/2011/563) of 19 September 2011 – 1st Situation Report on Training and Education in the nuclear energy field in the European Union, SEC(2011)1046 final
- Mutual Recognition Arrangement of the Comité International des Poids et Mesures (CIPM MRA) of 14 October 1999 on the mutual recognition of calibration and measurement certificates between national and international metrology organisations, signed by JRC-IRMM
- Design and Construction Code for mechanical equipments of innovative nuclear installations (CWA 16519:2012 – CEN Workshop Agreement compiling modification requests intended to be part of the revision of the RCC-MRx design code edition 2012)

3.1 Structural materials

The structural integrity of mechanical components in nuclear reactors must be guaranteed to ensure their safety. These components are exposed to exceptionally harsh environments due to a combination of high temperatures and stresses, corrosive coolants and intense radiation. Such a setting is a significant challenge for present Generation II and III, and future Generation IV reactors.

The main issues for structural components of water cooled reactors are related to life-extension beyond the original design life (typically 40 years) and possibly to power up-rates. These need to be addressed by understanding, predicting and mitigating ageing mechanisms such as stress corrosion cracking and radiation damage. Water cooled reactors that are currently being built will operate under similar conditions as Generation II reactors, and as such advantage can be taken of the vast available operational experience, extending the design life from 40 to 60 years. Moreover, the safety requirements will be higher and additional obligations may have to be imposed (for instance for the load-following capacity).

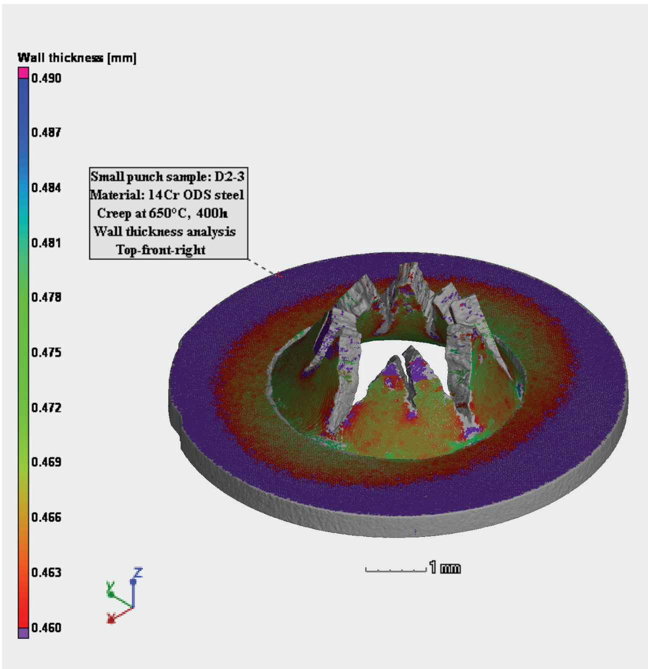
The components and materials in Generation IV reactor designs will generally be exposed to higher temperatures, significantly higher levels of radiation fluxes and new coolants that interact in a different way. They will probably be designed for a lifetime of at least 60 years. The prototypes for reactors investigated within the European Sustainable Nuclear Industrial Initiative (ESNII) will be based on commercially available materials such as austenitic steels and ferritic-martensitic steels, but these need to be qualified for harsher conditions.



Preparation of the small punch test set-up: a semi-non-destructive miniature test to determine material properties.

Developing design codes and best practice procedures (in particular for creep and fatigue under high temperatures) form the focus of the JRC's structural materials research, together with the development of non-destructive test and virtually non-invasive techniques and standards, of novel experimental techniques to investigate stress corrosion cracking in representative environment, of physics-based models with special emphasis on the grain-scale by strain-gradient crystal plasticity models; of web-based systems for data sharing and preservation; and on the assessment of the integrity of welds with special emphasis on residual stress measurements. The JRC is playing a very active role in Sustainable Nuclear Energy Technology Platform (SNETP) and the research networks for water cooled reactors (NUGENIA), fast reactors (ESNII and European Energy Research Alliance Joint Programme on Nuclear Materials - EERA JPNM), and co-generation heat and electricity (NC2I), for which roadmaps and joint research programmes are being implemented.

Due to their superior high temperature strength and corrosion resistance, Oxide Dispersion Strengthened (ODS) steels are candidate materials for future nuclear reactor applications. Based on previous experience with the development of the CEN Workshop Agreement (CWA 15627) on the Small Punch Test Method for Metallic Materials, the JRC has used this small-specimen test method to assess the creep and fracture performance of various commercial and experimental ODS steels. The ferritic ODS steels were shown to exhibit strong anisotropy in both their creep resistance and their ductile versus brittle behaviour as a function of temperature. The anisotropy in mechanical performance combined with a pronounced susceptibility to thermal embrittlement represent limitations regarding potential applications of ODS steels in safety-critical components.



Outcome of the small punch test: X-ray of ODS (Oxide Dipersion Strengthened) steel. The colours represent the thicknesses of the deformed disc.

Work in progress

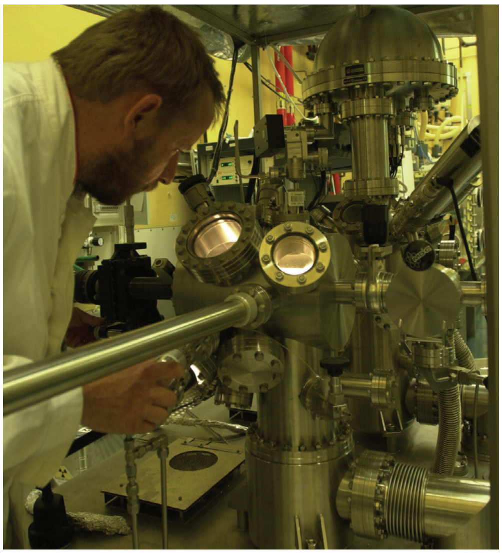
The JRC is developing methodologies to predict long-term material property degradation through accelerated tests, with extrapolation to operational conditions via physics-based models, as well as degradation resistant materials with respect to temperature, irradiation and corrosion. In addition, it is further developing design codes and assessment procedures to address new problematic domains such as environmental degradation of components, as well as the interaction between different mechanical loading modes.

The JRC is also integrating its research closely with national research programmes towards a European nuclear research platform for the integrity of systems, structures, components and materials, and accelerating innovative solutions and new products by incorporating the industrial application closer into basic research.

3.2 Actinide materials

Nuclear power is an established technology that can help satisfying increasing energy needs at global level. However, in many countries, issues about nuclear reactor safety, waste management and proliferation raise deep concerns about sustainability. Materials research can provide the means to solve, or at least mitigate, the main problems associated with the deployment of nuclear power plants, minimising risks and improving safety standards.

Actinide materials form the nuclear reactor core and are an important component of the materials to be treated when managing the nuclear fuel cycle. Knowing the properties of actinides and the consequences of their interaction with the materials that form the reactor structure (the walls, the coolant, the cylindrical tubes that house the fuel pellets, etc.) is key for establishing models that are able to predict - in a reliable and accurate way - the phenomena that may compromise operational safety, and thus to prevent them. However, theoretical models still do not match the complexity and variety of the interactions involving actinide atoms and the available experimental information is far from complete, which makes this a difficult task. JRC research on actinide materials contributes to filling this knowledge gap. A wide range of experimental techniques are used to measure macroscopic quantities (like thermal and electrical conductivity, heat capacity, mechanical and magnetic characteristics, melting and behaviour, and phase transformations), and to investigate, at microscopic level, spatial and temporal correlations between atoms. These correlations determine where the atoms are and how changing the state of one of them perturbates the state of all the others. Experimental data are then used for the development of comprehensive theoretical models providing a quantitative correspondence between microscopic observations and macroscopic properties. The types of investigated materials include organo-metallic complexes, ceramic compounds, halides, and inter-metallic systems. Experiments making use of quantum beam probes (electrons, photons, neutrons) are used to investigate surface and bulk properties as a function of external parameters, such as temperature, pressure, or magnetic field, spanning a wide range of values. For instance, temperature measurements can be performed from a few thousand degrees down to 0.5 degrees above absolute zero.



Surface science laboratory installation at the JRC.

Amongst the few research centres in Europe with a licence for handling transuranium compounds, the JRC is the only one offering the opportunity to the European academic community to carry out comprehensive experimental investigations of actinide materials. Its laboratories are open to the European academic community for the execution of studies selected by an independent committee on the basis of scientific merit. As research opportunities in this field are diminishing across Europe, the JRC represents a unique location in the European Research Area for maintaining required competences in this strategically important domain.

Uranium dioxide (UO_2) is used as fuel in nuclear reactors. Its macroscopic behaviour is well documented, but all aspects of its performance, reliability, and safety are still largely based on empirical data. The major obstacle for developing first-principles safety assessment models is the complexity of its physics at an atomic level. For instance, the transfer of heat across a fuel element is determined by the oscillations of uranium and oxygen atoms about their positions in the UO_2 lattice. In turn, these oscillations are strongly influenced by how the electrons behave, that is how they are distributed in space and how they interact with each other. Both of these points have been clarified by a combined experimental and theoretical study carried out at the JRC.

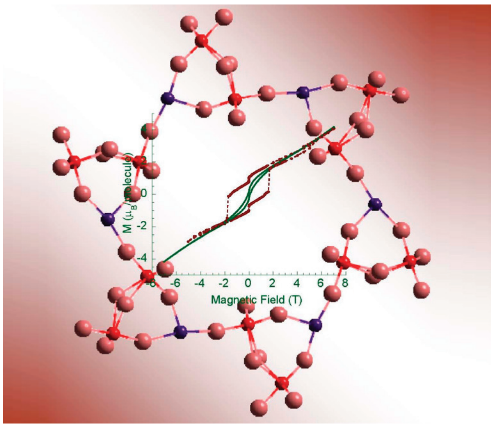
Researchers have discovered that the electronic clouds surrounding the uranium ions in UO_2 have the shape of a pancake (in physical terms, the uranium ions carry an electric quadrupole moment) and order in space at low temperature with a motif that pushes the oxygen ions away from ideal positions. Oscillations of these electric quadrupoles, propagating as waves along the crystal, have been directly observed by measuring the energy lost by neutrons fired at an UO_2 target.

These experimental findings have led to the development of a comprehensive theory showing that quadrupole waves affect the vibrations in the crystal lattice, which in turn determine a large part of the thermal conductivity.

Researchers presumed that quadrupole waves existed for a wide class of materials in connection with unconventional forms of superconductivity, but despite intensive research efforts it was never demonstrated. These quadrupole collective excitations represent a new form of elementary excitations in solids that could give rise to exotic collective behaviours with unexpected technological potential.

Work in progress

The JRC is currently performing research on physical properties of actinide elements and compounds under extreme temperatures, pressures and magnetic field conditions; it is studying the physical-chemistry of surfaces and interfaces of model fuel materials and the chemistry of organoactinide complexes. It is also investigating high-temperature thermodynamic properties and phase diagrams of actinide materials, with emphasis on oxides and carbides and the radiation effects on vibrational and thermal properties of actinide dioxides.



Single molecule magnet behaviour of a wheel-shaped uranium cluster.

3.3 Nuclear data

For the safety licensing process, a very detailed modelling and simulation of reactor behaviours in normal and accidental conditions is needed. This is extremely complicated as modern nuclear energy systems employ a variety of reactor types, and energy conversion and fuel cycle technologies, each of which use different coolants and structural materials.

In essence, any model simulating the behaviour or the safety of a nuclear energy system evaluates the production, transport and interaction of neutrons. All important aspects related to safety, such as reactor kinetics, nuclear criticality, heat production, induced radioactivity, radiation damage, and fuel radio-toxicity result from interactions between neutrons and nuclei. They define the sources of radiation, the radiation levels in different areas of the facility, the effect on people and materials, the nature and amount of nuclear waste, the activation of irradiated materials, and the safety margins that must be applied.

Rapid progress in computer technology made advanced simulation techniques increasingly precise. The accuracy of nuclear safety calculations now largely depends on the accuracy of nuclear data.

These data, which cannot be calculated but must be measured with the utmost accuracy, basically describe the behaviour of all possible interactions between particles and nuclei as a function of their energy.

They are also needed for the design and safety evaluation of irradiation facilities; fuel fabrication and waste management installations; equipment used for nuclear safeguards; industrial and environmental purposes and applications in medicine, such as the optimisation of doses during irradiation treatments of cancers, or the protection of patients and personnel during nuclear medicine diagnostics.

Only a few facilities worldwide are able to deliver nuclear data with the required accuracy. In Europe, the major facilities are the international laboratory of CERN in Switzerland and the JRC whose infrastructure includes the Van de Graaff and the GELINA particle accelerators. GELINA is specially designed for high-resolution nuclear data measurements, and has the best energy resolution in the world for these types of measurements.

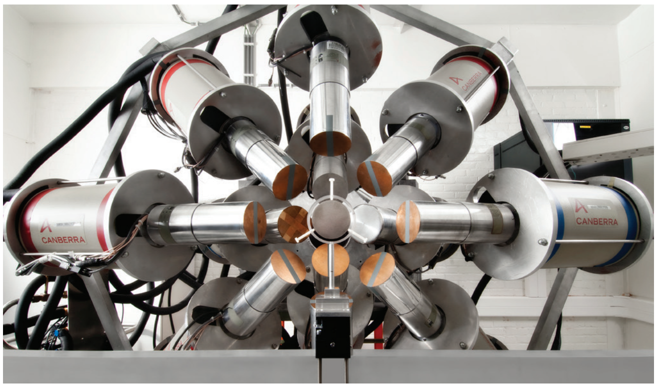
GELINA (Geel Linear Accelerator) is a unique accelerator facility for the production of neutrons located at the JRC in Geel (Belgium).

The Japanese Atomic Energy Agency (JAEA) selected a JRC-developed method as one of the most suitable approaches to characterise molten fuel originating from severe nuclear accidents such as at the Fukushima nuclear power plant. This characterisation is an international obligation during the decommissioning phase, according to IAEA safeguards. Japanese researchers are now developing and optimising the methodology to quantify special nuclear materials in particle-like debris of the molten reactor fuel.

Work in progress

The JRC is strengthening its role as major provider of reference nuclear data for nuclear energy applications in Europe, and it puts the focus on cooperation with stakeholders in Europe and worldwide.

It aims for example to substantially contribute to CIELO, an international collaboration between nuclear data experts for the worldwide standardisation of evaluated nuclear data, used for harmonised safety assessments in nuclear energy. The JRC is also working on its contribution to a new IAEA nuclear reaction data standards evaluation to enhance nuclear data quality assurance. The quality of neutron data standards is a key issue for improved safety of present day and innovative reactor systems.



GAINS spectrometer for nuclear data measurements.

3.4 Radioactivity measurements

The JRC is specialised in performing reliable radioactivity measurements, and contributes to the harmonisation of the results throughout Europe. Reliable measurements of α-, β- and γ- radiation are not only of great importance for nuclear safety and security but also for food safety, environmental monitoring and medical diagnosis and treatment. Indeed, all Member States have nuclear installations or make use of radioactive materials, particularly for medical purposes.

The JRC performs primary standardisations of radioactivity (the most accurate type of measurements) independent of any other radioactivity standard. It supports the work of international organisations such as the Comité International des Poids et Mesures (CIPM) in providing a proper means of calibration for any activity measurement anywhere in the world. It organises and participates in key comparisons to establish international equivalence of radioactivity standards. This direct link to the international standards enables the JRC to determine traceable reference values for its certified reference materials and for proficiency test samples used to ensure the quality of radiation monitoring results obtained by Member State laboratories.

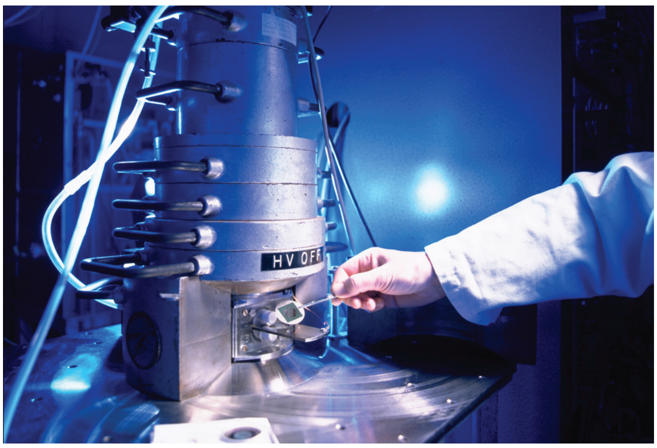
To measure the lowest radioactivity levels, the JRC performs low background measurements in a 225m deep underground laboratory 'high activity disposal experimental site' (HADES) at the Belgian Nuclear Research Centre (SCK-CEN). There the cosmic ray flux is ~10,000 times lower than above ground and consequently, the background noise for the instruments is also ~10,000 times lower enabling measurements of radioactivity that cannot be measured above-ground.

HADES underground laboratory.

This technique was initially employed in fundamental physics to study rare events but has been developed by the JRC into other fields of application such as environmental radioactivity and radioprotection in support of EU policies. Radiation emitted by certain radionuclides provides a 'fingerprint' by which specific processes in industry and the environment can be traced. For environmental and many other types of samples with very low activity, underground gamma-ray spectrometry can be used. In the past 15 years, the JRC has performed underground measurements for about 200 different projects. Examples are the characterisation of reference materials for their radioactive components; the determination of ^{60}Co (cobalt-60) in steel samples from Hiroshima; and the measurement of water samples from the Pacific Ocean after the Fukushima accident.

Good knowledge of the decay properties of radionuclides is also indispensable. There are more than 3000 radionuclides and all decay in different ways. Not many laboratories possess the equipment for high accuracy measurements. The JRC uses its unique infrastructure to improve the accuracy of decay data of radionuclides. Its high-quality reference measurements contribute to better quality assurance for example in radioactivity measurement laboratories worldwide; in safe use of radionuclides in novel medical treatments and in more precise assessments of the environmental impact of radioactivity; on improved tools for nuclear safeguards, on a stronger foundation for geochronology based on the decay of long-lived natural activity; on access to nuclear properties of importance to nuclear science and astrophysics and proper uncertainty assessments.

The JRC has recently developed a certified reference material for ^{40}K (potassium), ^{137}Cs (caesium) and ^{90}Sr (strontium) in dried bilberries, which can work as calibration or validation sources for radioactivity measurements of many types of food and feed. This reference material will be used by food control laboratories to ensure quality of their data. Its direct link to the international standards for radioactivity allows the JRC to issue reference materials with proven traceability and small uncertainty of its certified property values. Moreover, the JRC completed precision work on alpha-particle emission probabilities of two isotopes of uranium, ^{238}U and : some uncertainties were improved by two orders of magnitude.



JRC high-resolution alpha particle laboratory.

Work in progress

To strengthen its role as provider of reference decay data, the JRC is constantly improving its radionuclide measurement methods. It collaborates with the leading European measurement institutes and prioritises new measurement projects addressing the needs of EU policies, based on requests from the nuclear data section of the IAEA and the international decay data evaluation project.

As the updated Euratom basic safety standards address a more rigorous characterisation and radionuclide-specific identification of naturally occurring radioactive materials (NORM), the JRC will start conducting research in this field.

3.5 Standards for safeguards

Nuclear safeguards activities are based on international agreements and in the EU they are defined in the Euratom Treaty. The Non-Proliferation Treaty requires signatory states to provide detailed accounting records for their fissile materials, the non-diversion of which is verified by independent measurements.

The JRC provides safeguards authorities and the nuclear industry with standards for environmental sample analysis and for measurements of samples from all stages of the nuclear fuel cycle. It is also actively supporting the nuclear measurement community in applying the latest international standards in practices of conformity assessment to underpin confidence in safeguards results and decisions. This support includes material standards in the form of reference materials and measurements; European and international documentary standards; international guidelines, documents and tools on conformity assessment, including target performance criteria; and international platforms for exchange on needs for standards in safeguards.

Certified reference materials are used in method and instrument validation, and conformity assessment. They are indispensable for the transparency, traceability and accuracy of measurement results. In particular, measurements of uranium and plutonium isotope ratios at proliferation-sensitive stages, such as enrichment and reprocessing of nuclear fuel, help nuclear safeguards authorities trace the sources of nuclear material and investigate the diversion of nuclear material for non-civil purposes.

Large sized dried spikes are a fundamental part of fissile material control.

Under the Euratom safeguards system regular inspection activities are held. Measurements during these inspec tions have to stand in court and are therefore carried out with the highest quality nuclear reference materials and methods, of which the JRC's large sized dried (LSD) spikes IRMM-1027 series is one example. They are used for the determination of uranium and plutonium content of spent fuel solutions at the Euratom safeguards on-site laboratories at the reprocessing plants of Sellafield in the UK and La Hague, France. Achieving the required high level of detection probability is a major challenge, enabled by the JRC LSD spikes.

The analysis of uranium particles, which is addressed in the additional protocol to the Non-Proliferation Treaty, has become one of the most powerful tools to detect undeclared nuclear activities. Sophisticated mass spectrometry techniques now allow the direct investigation of the isotopic composition of uranium and other chemical elements in micro-metre-sized single particles found on environmental swipe samples taken by safeguards inspectors. The JRC-organised inter-laboratory comparisons, which confirmed the capability of European Safeguards and the IAEA network analytical laboratories for environmental sampling in measuring isotope ratios in uranium particles of the size below 1 μm diameter.

The JRC has developed and improved methods for routine uranium isotope ratio measurements using the modified total evaporation for multi-collector thermal ionisation mass spectrometry (MTE-TIMS) and for accurate isotopic measurement of uranium hexafluoride (UF_6). Accurate measurements of the major and minor isotope ratios of uranium are important as they give an indication to safeguards authorities of, the type of 'feed' materials, of the enrichment process, and the 'history' of nuclear material. As a consequence of these recent analytical advances the JRC is suggesting the revision of existing uranium documentary measurement standards for measurements of UF_6, and the development of a new standard based on MTE-TIMS.

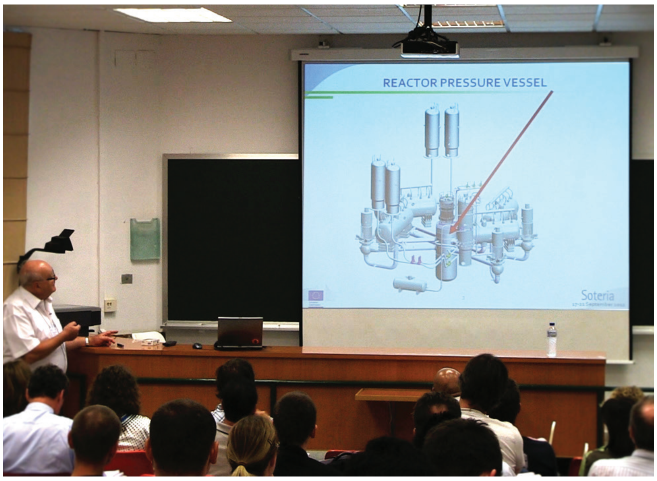
Reference measurements of UF_6 samples from enrichment plants.

Work in progress

In light of new challenges such as nuclear disarmament which will require harmonisation across different cultures, the JRC aims to provide valuable input for the development and implementation of standards for safeguards at international, national and regional levels.

4 Nuclear knowledge management, training and education

The Euratom Treaty states that "the Commission shall be responsible for promoting and facilitating nuclear research in the Member States and for complementing it by carrying out a Community research and training programme". Education and training (E&T) in the nuclear field has therefore always been an integral part of the JRC's work. With its activities the JRC supports the strong unanimous understanding among the 28 Member States to invest in nuclear safety and security research and cross-cutting activities such as training and education, in order to ensure that top-level competence and expertise for nuclear safety assessments are available in the EU.



Training course organised by the JRC.

Education and training in the nuclear field must also be considered a key component of the international nuclear infrastructure in order to maintain high levels of nuclear safety, as stated by both the Council of the European Union and the 2009 G8 summit. However, organisations such as OECD/NEA and IAEA have raised concerns about the current nuclear education and training level.

The JRC's current E&T efforts are diverse and can be grouped in three major activities: (a) nuclear knowledge management (b) contribution to the European E&T activities, by hosting students and organising internships and specialised training courses in the fields of nuclear safety, safeguards, security and forensics and (c) monitoring the human resources development in the nuclear field in Europe.

JRC activities in this area provide scientific support to the following policy initiatives:

- Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste
- Directive 2009/71/Euratom of 25 June 2009 establishing a Community framework for the nuclear safety of nuclear installations
- Council conclusions from 1 and 2 December 2008 on the need for skills in the nuclear field
- Commission Staff Working Paper accompanying the Communication (COM/2011/563) from the Commission of 19 September 2011 – 1st Situation Report on Training and Education in the nuclear energy field in the European Union, SEC(2011)1046 final
- European Council conclusions of 25 September 2008 on standardisation and innovation

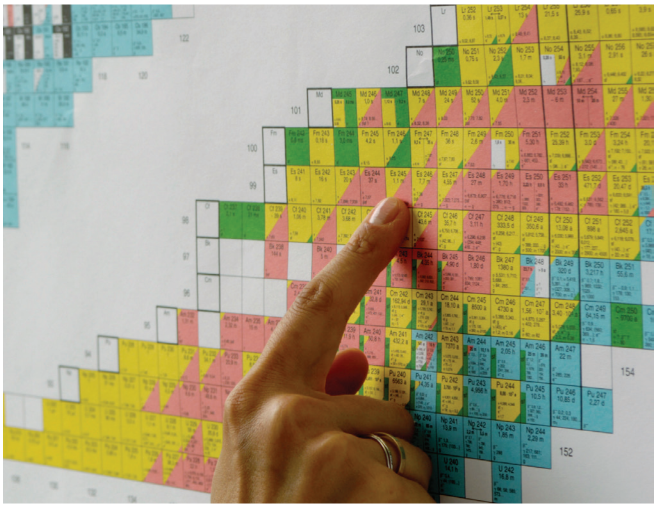
4.1 Nuclear knowledge management

The JRC carries out work in the nuclear knowledge management field by developing guides and multimedia training modules for knowledge preservation, consolidation and transfer; the establishment of international practice communities, knowledge capture, knowledge dissemination and outreach.

The JRC develops training and education tools in various nuclear energy fields; they target different types of users, ranging from experts that need in-depth training on particular topics, to the general public and media outlets. The focus of these tools is to deliver quality content in a modern and appealing way, using modern technologies such as online multimedia and augmented reality in order to engage as wide an audience as possible.

The JRC updates the Karlsruhe Nuclide Chart, a living periodic table displaying all known isotopes of all elements and their radioactive data in a distinctly easy to navigate colour scheme. The Karlsruhe Nuclide Chart has been tracking new elements since 1958 and is the product of a longstanding partnership between the JRC and Karlsruhe Institute of Technology. Its history charts the discovery of new elements and decay models, neutrinos, quarks, antimatter and dark matter.

An updated edition has been published in 2012 and contains new and updated radioactive decay data on 737 nuclides not available in the previous edition, dating from 2007. In total, nuclear data on 3847 nuclides are presented. The new edition includes the new element names copernicium (symbol Cn, element 112), flerovium (symbol Fl, element 114) and livermorium (symbol Lv, element 116), as recently approved by the International Union of Pure and Applied Chemistry (IUPAC). It also provides the most recent values of the atomic weights and isotopes abundances and other various nuclear parameters.



The Karlsruhe nuclide chart.

The JRC also created Nucleonica, a software used by professionals for everyday calculations, for obtaining quick results and testing, or for validating and verifying complex computer models. It employs cloud applications and IT tools within an integrated know-ledge environment. A collaboration platform is at the core of a community of students and professionals where users not only access information individually, but can also interact.

Nucleonica and the Karlsruhe Nuclide Chart compile and make scientific data freely available in an educational, 'live' format which makes use of web crawlers, rss feeds, along with a discussion forum, a blog, a wiki and numerous tutorials. The approach to both tools is minimising the effort needed to find, access and process extensive amounts of data in real time.

Work in progress

The JRC is contributing to the soon-to-be-published IAEA safety guide on nuclear knowledge management and development of a knowledge management strategy and its implementation in nuclear organisations.

The JRC is further developing – also in collaboration with the IAEA – an online multimedia tool to summarise the lessons learned from the three major nuclear accidents: Fukushima, Chernobyl and the Three Mile Island. The tool focuses on three phases: emergency planning, preparedness and response; people and their protection (radiation protection and evacuation in case of a nuclear accident) and post-accident measures for people and the environment.

The JRC is also organising two workshops for candidate countries, new Member States and Horizon 2020 associated countries, to disseminate the results of their research through education and training.

4.2 JRC training programme on Nuclear Safety and Security

Taking into account the long-term prospects of nuclear power production, expertise is needed in all domains of nuclear technology for many decades to come. This includes waste management and decommissioning, but also the broad field of safety and security of current and future reactors.

The JRC training programme on Nuclear Safety and Security is one of the JRC's answers to the diminishing opportunities for students and young professionals to gain hands-on experience in working with nuclear materials. Indeed, facilities to handle nuclear materials are not located in academic institutions but in national and international research institutions, where a high level of safety and security must be guaranteed. The key goal of the programme is to create better access to nuclear research facilities, while facilitating the E&T programmes of Member States and pan-European organisations. By providing its expertise in the nuclear field, the JRC actively contributes to improving educational tracks, in collaboration with leading European universities and educational institutions.

The programme consists of four pillars: higher education, vocational training, user access and information dissemination. For the first pillar JRC staff contribute to academic courses and special educational activities such as summer schools and inter-semester courses. Its key components are the grantholder and trainee programmes through which students are hosted at the JRC nuclear facilities for several months to three years.

The vocational training focuses on young professionals, many of whom have no specific expertise in the nuclear domain when initially hired, and is being developed with partners from the European GENTLE project (Graduate and Executive Nuclear Training and Lifelong Education under the FP7 Fission Training Scheme) and with other European educational institutions. The user access programme offers short-duration opportunities for researchers who can perform dedicated experiments on nuclear data, radioactivity measurements, nuclear materials, or materials relevant to nuclear technology, which are not possible in their laboratories.

Finally, the programme information centre provides independent information about nuclear science and technology to the general public.

The JRC has launched a transnational access programme, called EUFRAT (European facilities for nuclear reaction and decay data measurements) to facilitate the access of outside researchers to its nuclear data facilities. In a period where the nuclear research community is confronted with a declining number of young researchers the EUFRAT project tries to attract young people into entering the nuclear data research field. EUFRAT offers new nuclear scientists and engineers unique training opportunities so that they can prepare for their PhD studies, enabling them to continue this type of research in the future. More than 100 researchers from the Member States participated in the experiments, of which 25% were young students.

Apart from training programmes, the JRC also developed training and education tools. Notable examples are the online multimedia module, developed in collaboration with the IAEA, for training in the field of reactor pressure vessel embrittlement of the water-water power reactor (WWER) and for learning how to best carry out WWER integrity assessments, an online Frequently Asked Questions repository to explain the basics of nuclear energy to the general public, and an animated tool for school-aged children to explain how nuclear energy works.

Nuclear courses WWER.

Work in progress

The JRC has launched courses and student research projects in the framework of the GENTLE project's programme. This includes inter-semester courses for graduate and post-graduate students studying specific topics that are generally not part of the academic program. Examples are courses in the field of nuclear safeguards and forensics, nuclear fuel, and nuclear data.

4.3 Monitoring human resources in the nuclear energy sector

The European Human Resources Observatory in the Nuclear Energy Sector (EHRO-N) was set up by the European Nuclear Energy Forum (ENEF), an initiative of DG ENER. Since its official launch in 2011, EHRO-N has been operated by the JRC to provide qualified data on human resource needs in the nuclear field and high-level expert recommendations on EU-wide nuclear E&T actions, promoting lifelong learning and cross border mobility. The JRC ensures the effective communication, cooperation and impartial operation of EHRO-N. It provides for example the necessary infrastructure and networking contacts, ensuring long-term stability, collects data and high level expert recommendations and maintains relations with other similar national and international organisations.

EHRO-N's senior advisory group (SAG) is composed of highly-qualified experts representing approximately 30 organisations worldwide. It provides general guidance on conceptual issues such as the type of data and data quality required, the analysis to be performed, the endorsement of major human resources-related reports and the preparation and execution of major communication campaigns.

All EHRO-N reports are available on a public website, which also includes other interesting features regarding nuclear training, education and stakeholders.

The JRC has for the first time mapped all nuclear stakeholders in the EU, from both the supply (universities, academies, training providers, etc.) and demand side (operators, manufacturers, regulators, etc.). It analysed the human resources situation in the nuclear energy sector, contacting all stakeholders and calculating the HR needs under the assumption of two nuclear energy demand scenarios.

The bottom-up report showed that there is a 30% gap in nuclear human resources, which is presently covered by the industry with in-house nuclearisation of other engineering graduates; the top-down analysis indicated that the expected future nuclear capacity to be installed is significantly lower than in the 1980s, but that a steep rise in construction is to be expected due to additional power plants, replacement of the current reactor park and the extension of the lifetime of current reactors. The JRC is keeping up its efforts to ensure this information is up-to-date and a second survey is already ongoing.

Another key message is that a successful implementation of the European Credit system for Vocational Education and Training (ECVET) in the nuclear energy sector will lead to a better future analysis of the gap in knowledge, skills and competences.

Work in progress

EHRO-N is promoting its methodology in non-EU countries, in order to achieve a global mutual recognition system. It is also actively supporting the implementation of the European Credit System for Vocational Education Training (ECVET) in the nuclear energy sector, by organising seminars for stakeholders and establishing a job taxonomy based on the knowledge, skills and competences framework for nuclear professions in the area of design, operation and decommissioning.

5 Fostering the innovation flow

The JRC's innovation activities in the nuclear field are focused on the following areas: materials for new reactor technologies, transmutation techniques, safeguards and safety for innovative reactor designs.

JRC activities in this area provide scientific support to the following policy initiatives:

- Treaty establishing the European Atomic Energy Community (Euratom Treaty) – 1957
- The International Treaty on the Non-Proliferation of Nuclear Weapons of 22 April 1970 (INFCIRC/140) and associated Additional Protocol
- Fight against the proliferation of weapons of mass destruction - EU strategy against proliferation of Weapons of Mass Destruction (15708/03), adopted by the Council of the European Union on 10 December 2003
- Regulation No 428/2009 of 5 May 2009 setting up a Community regime for the control of exports, transfer, brokering and transit of dual-use items (Recast)
- Decision no 14929/05 of 20 December 2005 concerning the approval of the accession of the European Atomic Energy Community (Euratom) to a Framework Agreement for International Collaboration on Research and Development of Generation IV International Forum Nuclear Energy Systems
- Decision C(2002)4287 of 4 November 2002 for the European Atomic Energy Community to (1) adhere to the Generation IV International Forum, and (2) to conclude a technical exchange and cooperation agreement and the Department of Energy of the United States of America
- Communication from the Commission of 26 March 2009 on nuclear non-proliferation, COM/2009/0143
- Communication from the Commission of 15 December 2011 - Energy Roadmap 2050, COM(2011)885
- Communication from the Commission of 22 November 2007 - A European strategic energy technology plan (SET Plan) - Towards a low carbon future, COM(2007)723
- Council conclusions on strengthening chemical, biological, radiological and nuclear (CBRN) security in the European Union - an EU CBRN Action Plan, 15505/1/09 Rev.1
- Strategic Research and Innovation Agenda of the Sustainable Nuclear Energy Technology Platform
- Joint Programme on Nuclear Materials of the European Energy Research Alliance

5.1 Innovation in materials

New technologies for future nuclear reactors, like the fast reactors and high temperature reactors, envisage extended service lives of up to 60 years, with components exposed to unexplored or unqualified environments, such as higher temperatures and variable thermo-mechanical loads, new coolant environments, and high dose irradiation by fast neutron spectra. Structural materials are crucial for a safe nuclear technology, hence innovative technological solutions and surveillance concepts for materials selection and component design are needed for these new operating conditions.

Today, however, the existing materials testing standards and design codes do not meet all the requirements for future operating conditions. The JRC contributes to closing this technology gap by performing pre-normative R&D and transferring it into codes and standards which are needed to assess structural integrity. Focus is also placed on novel test techniques for rapid screening and accelerated testing of materials, advanced inspection procedures and innovative materials data management to promote harmonisation.

The JRC carries out performance and reliability assessments of structural materials and components at laboratory scale, in particular materials testing with respect to thermo-mechanical performance, corrosion and irradiation resistance, taking into account high-temperature coolant compatibility and long-term operation. Advanced materials degradation and component inspection procedures, including the integrity assessments of welds, are also performed using the JRC's state-of-the-art experimental facilities.

JRC transmission electron microscope facility for advanced material studies.

The JRC further promotes the development of codes-of-practice and standards for novel test techniques. For example it advocated a standard for small-specimen testing, and has contributed to advancing a European Design Code for future nuclear facilities, by taking part in a feasibility study on the need for standardised design and construction rules for future nuclear reactors.

These activities are combined with advanced materials data management tools to promote harmonisation, preservation and re-use of materials data generated through European R&D programmes, as well as physics-based modelling and simulations to understand the interaction between the microstructure of materials and their overall performance.

JRC R&D activities are closely aligned with the industrial initiatives defined within the Sustainable Nuclear Energy Technology Platform (SNETP), and are integrated into the joint programme on nuclear materials of the JRC and the European Energy Research Alliance. Moreover, with its results from scientific R&D, the JRC fuels the strategic debate about nuclear R&D both at the European and international level.

The JRC has developed MatDB, an online materials database, which hosts materials data from various European R&D programmes as well as, for example, the comprehensive IAEA surveillance databases for the embrittlement of pressure vessel steels. It contains over 40,000 test results coming mainly from European R&D projects and provides a web-interface for data content, data entry, data retrieval and analysis routines. MatDB has been under continuous development and use for more than 30 years, evolving from a simple desktop application into an advanced online system.

Through this tool, the JRC promotes standardisation for preserving and exchanging materials data.

MatDB has recently been enabled to use digital object identifiers (DOIs) for data publication. Assigning DOIs to datasets and publishing them in much the same way as conventional scientific publications provides the opportunity to promote data preservation, sharing, and reuse. The benefit to researchers is that their datasets can be cited in derivative works. Importantly, while promoting the work of researchers, data publication does not imply that data is freely accessible. Instead, if a dataset is restricted or confidential, then only some limited information will be visible.

For project partners who have generated data and who are planning to report their results in a scientific publication, this means there is the possibility to assign DOIs to datasets and reference them in the bibliography in exactly the same way as references to conventional publications.

Work in progress

The JRC is working on the scientific base for European standardisation, and is further strengthening its pre-normative research efforts in energy technologies. It will also continue its contribution to safety and feasibility assessments of innovative nuclear reactors through own work and European projects addressing the qualification of existing materials as well as the performance assessment of new materials with respect to high temperature creep, fatigue and corrosion resistance.

5.2 Innovation in fuels

Europe's nuclear reactor fleet is mainly fuelled with uranium oxide (UO_2) which on discharge from the reactors contains various toxic species including the particularly important long-lived (longer than 100,000 years) minor actinides neptunium, americium and curium. To limit their potential risk to the environment, the JRC investigates the transformation of minor actinides into short-lived (around 500 years) species in dedicated reactors. Novel new fuels are synthesised to determine fundamental safety properties, such as thermal conductivity, melting point, vaporisation behaviour, enabling initial assessment of their safety during operation in nuclear reactors.

JRC minor actinides laboratory.

Such fuels should optimise the transmutation efficiency and also circumvent potential safety issues related to helium which is generated in large amounts in these very special fuels. Along with the laboratory investigations, the JRC has teamed up with other European laboratories to perform safety tests on these new fuels in the High Flux Reactor (HFR) in Petten and the Phenix reactor. The results are continuously integrated in the JRC's modelling tools, such as TRANSURANUS.

The JRC has synthesised innovative fuels to study the safety of minor actinide fuels in irradiation tests in reactors in France and the Netherlands. These fuels were composed of $(Pu, Am)O_2$ [plutonium, americium-dioxide] particles and $(Zr, Pu, Am)O_2$ [zirconium, plutonium, americium-dioxide] particles embedded in a molybdenum matrix, as a novel means to reduce the operating temperature of the fuel and thereby to enhance the safety margin to the melting of the fuel. The irradiation experiment itself and the examinations thereafter indicated excellent behaviour. Eventually such fuels can be foreseen in dedicated reactors, such as in the Myrrha project in Belgium or ASTRID in France.

Should uranium sources ever be short in supply, fuels based on thorium could be considered as a sustainable option to meet energy demands. Thorium is a by-product from rare earth mining, and though not widely used today, it has the advantage that plutonium and minor actinides are far less abundant in the fuel after irradiation. As a first step in the safety assessment of such fuels at high burn-up, the JRC synthesised $(Th,Pu)O_2$ [thorium, plutonium-dioxide] pellets, which were irradiated in the KWO power plant in Obrigheim, Germany. The irradiation test was performed under representative conditions, and the fuel performed at least as well, if not better, than its classical $(U,Pu)O_2$ MOX [mixed uranium, plutonium dioxide] counterpart.

Work in progress

The JRC synthesises the highest quality samples and determines essential data (melting point, thermal conductivity, heat capacity, mechanical properties, etc) needed by Member State authorities to license the fuel. It undertakes separate effect investigations, over multiple time and distance scales, to unravel complex issues of nuclear fuel under irradiation (irradiation induced damage, gas transport, chemical evolution, mechanical constraints) in normal and accident conditions. The goal is to provide new models, backed by dedicated experiments, to be incorporated in fuel performance codes, which will have exceptional predictive capability, a necessity for all reactor licensing authorities.

To meet these goals, JRC scientists and engineers have found innovative ways to harness conventional scientific equipment to the stringent demands of a nuclear laboratory. Such unique facilities include laser melting point determination, electron microscopy and nuclear magnetic resonance spectroscopies to name but a few.

5.3 Innovation in safeguards

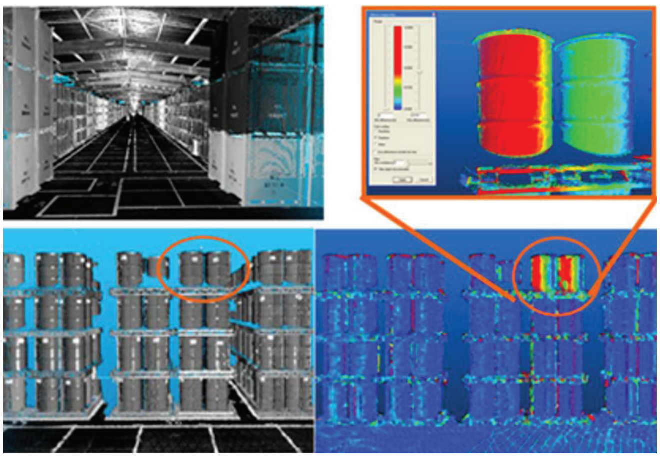
R&D in nuclear safeguards, non-proliferation and nuclear security is a cornerstone of the JRC's work on nuclear safety and security. The activities in this field aim to prevent or detect the misuse of nuclear fuel cycle technology for non-civil purposes.

In the verification domain, focus is set on high-quality systems for measurements during the enrichment process. Emphasis is also placed on process monitoring for example focusing on the front-end and back-end of the nuclear fuel cycle. Innovative 3D laser based techniques have been developed by the JRC for verification of tampering or modification of systems. At facility level, the emphasis is put on the monitoring and modelling of material flows, sealing techniques and unattended and remotely operated systems. Environmental sampling and other verification methods such as laser based methods and satellite imagery continue to pose challenges. To contribute to the evaluation and/or the verification of state activities and capabilities, open source analysis focused on trade of sensitive technologies offers significant potential.

In the field of nuclear safeguards, there is a strong demand for a robust and durable seal system to monitor, identify and verify containers used for under-water storage of nuclear spent fuel materials. Sealing and identification systems are also used for nuclear transportation casks, long term dry storage repository or other movable structures of strategic value, such as containers, weapons or explosives. The seals do not prevent access but give non-erasable, unambiguous evidence of opening or tampering.

The ultrasonic seals developed by the JRC are used to detect any opening of the container. The seals have artificial cavities manufactured to have a unique identity, a so-called 'fingerprint'. When opened or tampered with, the identity remains the same but the integrity has been broken, which is detectable with the ultrasonic reading system.

These ultrasonic seals are radiation resistant and extremely reliable, even in very harsh environmental conditions. They do not have electronic components and are made of stainless steel, giving them a very long lifespan. They are particularly suited for underwater applications but in the near future they will be used to seal dry storage casks as well. The JRC's ultrasonic sealing system is used by international organisations, such as the IAEA, for the control of nuclear materials.



3D laser application to verify changes in a storage facility.

In the context of the Support Programme to the IAEA, the JRC has also developed a laser-based system (3DLR) that creates accurate 3D models of nuclear facilities, both indoor and outdoor, and is able to detect any change to the nearest millimetre. 3DLR was introduced to support Design Information Verification (DIV) activities in large and complex nuclear facilities. The JRC has also developed the Laser Item Identification System (L2IS) to assist inspectors in identifying and tracking UF_6 cylinders during transit between process and storage areas at an enrichment plant. Both systems have successfully passed vulnerability assessments and have been authorised by the IAEA for routine safeguards use.

Work in progress

The JRC is developing advanced non-destructive assays (automated modelling for numerical calibration, alternative neutron detectors, gas centrifuge enrichment plant (GCEP) cylinder verification, spent fuel) and is performing destructive analyses of metallic impurities in special nuclear materials (SNM) and environmental sampling.

The JRC is also further developing tools for the advanced process monitoring of facilities and improving the identification and Design Information Verification (DIV) through 3D laser applications, image-reviewing tools, innovative seals, and open source information including satellite imagery and trade data.

5.4 Generation IV International Forum (GIF)

The Generation IV International Forum (GIF) has identified sustainability, competitiveness, safety, reliability, proliferation resistance and physical protection as the main criteria for the next generation nuclear reactor systems.

Six reactor concepts have been selected for further internationally coordinated R&D: the sodium-cooled fast reactor (SFR); the gas-cooled fast reactor (GFR); the supercritical water-cooled reactor (SCWR); the very high temperature reactor (VHTR); the lead-cooled fast reactor (LFR); and the molten salt reactor (MSR).

Each concept employs a variety of reactor, energy conversion and fuel cycle technologies. Their designs feature thermal and fast neutron spectra, closed and open fuel cycles, and the full range of reactor sizes. Depending on their degree of technical maturity, the Generation IV systems are expected to be commercially introduced between 2020 and 2030, or beyond. The JRC is contributing to safety-related research in materials and fuels, safety assessment of reactor designs, and in cross-cutting topics on several of these reactor concepts.

In addition, it has contributed in the safety-related fuel development programmes (e.g. technology, fuel/clad interaction) of the GFR, SFR, VHTR systems (in partnership with the FP7 GoFastR, ALLIANCE, CARBOWASTE projects), and has actively participated in the working groups linked to material R&D programmes (in partnership with the FP7 RAPHAEL/ARCHER projects).

Safety of Generation IV reactor designs has also been addressed by the JRC through the participation in dedicated FP7 projects (SARGEN_IV, LEADER, CP-ESFR, JASMIN), within the GIF Risk and Safety Working Group (Integrated Safety Assessment Methodology and guidance document), with a contribution to the development of the safety design criteria for the sodium-cooled fast reactor (SFR). Furthermore, in collaboration with the CP-ESFR (collaborative project for a European sodium fast reactor) consortium, the JRC is actively contributing to the GIF SFR steering committee, the safety design criteria task force (SDC-TF) and to projects on safety and operation, and system integration and assessment.

Within the Generation IV International Forum, the JRC has been actively contributing to the proliferation resistance and physical protection working group (PRPPWG). PRPPWG was tasked by GIF to develop a comprehensive methodology for the proliferation resistance and physical protection (PR&PP) evaluation of the Generation IV reactors. The resulting methodology has been made available to GIF and underwent a series of revisions to arrive in its final form.

The working group also produced a comprehensive case study applying the GIF PR&PP methodology to an exemplary sodium-cooled fast reactor (SFR) and joint study carried out by the PRPPWG and the six Generation IV systems steering committees. This joint study presents the main features of all the six Generation IV systems, highlighting the main aspects relevant for their proliferation resistance and physical protection robustness. The three resulting final reports are available on the public GIF website.

JRC’s nuclear facilities

1. Nuclear safety

- **Laboratory for the ageing of materials in light water reactor (LWR) environments (AMALIA):** The AMALIA laboratory for aqueous corrosion and stress corrosion cracking studies encompasses four recirculating water loops with 6 autoclave systems, including full water chemistry control, environmental mechanical testing facilities, electrochemistry, electric impedance, and acoustic emission monitoring, to assess coolant compatibility and materials degradation issues in light water reactor environments.

- **High Flux Reactor (HFR):** The high flux reactor is one of the most powerful multi-purpose materials testing research reactors in the world. The HFR is a tank in pool type light water-cooled and moderated and operated at 45MW. The reactor provides a variety of irradiation facilities and possibilities in the reactor core, in the reflector region and in the poolside facility. The HFR is owned by the JRC but operated by the Dutch Nuclear Research and consultancy Group (NRG).

- **Hot cells:** Complete set of facilities for handling and treating irradiated nuclear fuels and materials, and for performing detailed scientific investigations covering all aspects related to the safety of nuclear fuels during irradiation under normal and accident conditions.

- **Microstructural analysis laboratory:** Facilities for microstructural characterisation and materials degradation studies, including scanning, transmission electron and atomic force microscopy, 3D X-ray tomography, X-ray diffraction, thermo-electric power and Barkhausen noise measurements, and micro and nano-indentation hardness measurements.

- **Materials research laboratories:** Series of unique, mostly home-built experimental installations dedicated to the study of thermodynamic and thermo-physical properties of actinides and nuclear materials.

- **Structural Materials Performance Assessment laboratories:** Facility used for the mechanical performance characterisation, life assessment and qualification of structural materials for present and next generation nuclear systems. Testing capabilities include high temperature (thermo-)mechanical tests, low-cycle fatigue, creep and fracture mechanics tests, as well as miniaturised mechanical tests.

2. Nuclear security

- **Advanced safeguards, measurement, monitoring and modelling laboratory (AS3ML):** Laboratory to develop, implement and validate safeguards measures, to monitor the operation of facilities through an extensive collection of data from multiple types of sensors, and to model the plant operations in order to be able to analyse the data collected by the monitoring system. AS3ML is designed for the testing, developing, demonstration of and training on innovative integrated solutions for the implementation of safeguards in the different types of nuclear installations.

- **Large geometry secondary ion mass spectrometry laboratory (LG-SIMS):** Laboratory for searching traces of nuclear materials in particles collected on cotton swipes during nuclear safeguards inspections.

- **Laser laboratory for nuclear safeguards and security:** Laser based systems to carry out containment and surveillance techniques for nuclear safeguards, including fingerprinting of nuclear containers, change detection, design information verification systems and outdoor verification systems.

- **Nuclear trace and analyses facility:** Set of installations for the chemical, physical and spectroscopic analysis of actinide and nuclear materials.

- **Performance laboratory / Pulse neutron interrogation test assembly (PERLA / PUNITA):** Laboratory for the assessment and evaluation of performances for all non-destructive assay (NDA) techniques applied in the safeguards and security of nuclear materials. PUNITA incorporates a pulsed (D-T) neutron generator and allows active neutron interrogation to detect minute quantities of nuclear materials.

- **Tank measurement laboratory / Solution monitoring laboratory (TAME / SML):** Facility to develop measurement techniques for bulk handling facilities, where large quantities of materials are processed, through inventory quantification and density characterisation.

- **European nuclear security training centre (EUSECTRA):** Specific technical infrastructure where a wide range of nuclear materials is available, to enable unparalleled training opportunities in the field of nuclear security and safeguards. Training areas include border detection, train-the-trainers, mobile

emergency response, reach-back, creation of national response plans, nuclear forensics, radiological crime scene management, nuclear security awareness and sustainability of a national nuclear security posture.

3. Reference measurements, materials and standards

- **Certified nuclear reference materials laboratories** for the preparation and provision of certified nuclear reference materials and reference measurements; well-characterised targets for measurements in nuclear physics for nuclear safety and nuclear safeguards applications.

- **Fundamental properties of actinide materials under extreme conditions:** State-of-the-art installations designed for basic research on behaviour and properties of actinide materials under extreme conditions of temperature, pressure, external magnetic field and chemical environment. Surface science laboratory for synthesis, structural, and spectroscopic characterisation of model nuclear materials.

- **Fuels and materials synthesis and characterisation facility:** Shielded glove boxes for the synthesis and characterisation of actinide materials, including nuclear fuels.

- **Geel Linear Accelerator (GELINA):** A pulsed white spectrum neutron source with the best time resolution in the world. It is especially designed for the measurement of highly accurate neutron cross-section data. GELINA is a multi-user facility, serving 10 experiments simultaneously. Measurements at GELINA provide data which form the basis for a wide range of evaluated neutron cross-section data. These data are needed for the safety assessments of present-day and future nuclear energy systems.

- **High activity disposal experimental site (HADES):** Laboratory for ultra-sensitive radioactivity measurements 225 m deep underground.

- **Radionuclide metrology laboratories:** A cluster of instruments for high precision radioactivity measurements.

- **Tandem accelerator-based fast neutron data source (MONNET):** The MONNET facility is an electrostatic tandem accelerator for the production of continuous and pulsed proton-, deuteron- and helium ion beams. Mono-energetic beams of neutrons can be produced in DC mode and in pulsed mode. Measurements at the Tandem accelerator provide data which form the basis of a wide range of evaluated neutron cross-section data. The domains under study encompass safety of fission reactor and fuel cycle technology, high burn-up fuels, nuclear waste transmutation and innovative reactor systems.

5. Fostering the innovation flow

- **Sealing and identification laboratory (SILab):** Laboratory for the development, testing and commissioning of security systems based on innovative sealing technologies (ultrasound, fibre optics, electronics, etc.) for nuclear safeguards applications worldwide.

Useful contact

https://ec.europa.eu/jrc/en/contact/form

The JRC works in close contact with a vast array of institutions, research networks and science-led public and private partners and is continuously strengthening co-operations on global issues with international partners and organisations.

On the nuclear safety and security field, cooperation is developed world-wide, with close collaboration with universities, environmental ministries and agencies, nuclear safety and security authorities, international representatives from research and safety organisations, as well as regulators to achieve the highest safety standards in the operation of conventional, innovative and advanced fuels and fuel cycles. A representative sample of these partners can be found on this page.

Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile (ENEA), Italy - AREVA, France - ASTM International, formerly known as the American Society for Testing and Materials - Atomic Weapons Establishment (AWE), UK - Baden-Württemberg -Ministry of the Environment, Climate Protection and the Energy Sector, Germany - Border monitoring working Group (BMWG) - Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) - Brussels University (ULB), Belgium - Bundesamt für Eich- und Vermessungswesen (BEV), Austria - Bundesamt für Strahlenschutz (BfS), Germany - Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA), Germany - Bundeskriminalamt (BKA), Germany - Bureau International des Poids et Mesures (BIPM) - California Institute of Technology, Pasadena, USA - Central Research Institute of Electric Power Industry (CRIEPI), Japan - Centre d'Etudes Nucléaires Bordeaux-Gradignan (CENBG), France - Centre National de la Recherche Scientifique (CNRS), France - 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Abstract

This report provides a detailed overview of research on nuclear safety and security, including their policy background and context, as carried out by the Joint Research Centre (JRC), the European Commission's science and knowledge service. Organised in five chapters, the report describes relevant scientific output in nuclear safety; nuclear security; reference measurements, materials and standards; nuclear knowledge management, training and education and, in the last chapter, innovation.

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