FROM RESEARCH TO INDUSTRY

cea den

NUCLEAR ENERGY DIVISION

ACTIVITY REPORT

2015

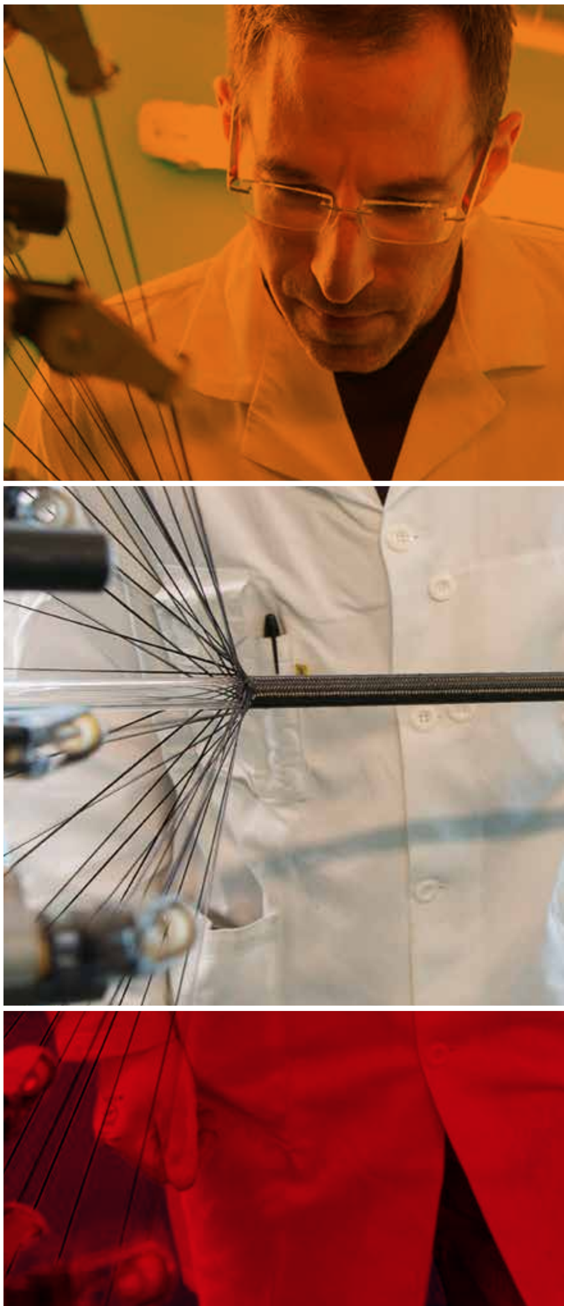
PROFILE

Within the CEA, the Nuclear Energy Division (DEN) provides the French government and industry with technical expertise and innovation in nuclear power generation systems to develop sustainable nuclear energy that is both safe and economically competitive.

To meet these objectives, the DEN is engaged in three main areas of investigation:

- Developing nuclear systems of the future - dubbed "4th generation" reactors - and their fuel cycles;
- Optimising the current nuclear industry;
- Developing and operating large experimentation and simulation tools needed for its research programmes.

As nuclear operator, the DEN also has to manage and upgrade its own fleet of nuclear facilities. It carries out numerous construction and refurbishment programmes on its facilities, together with clean-up and dismantling programmes for those that have reached the end of their service life.



CONTENTS

MESSAGE FROM FRANÇOIS GAUCHÉ

CEA DIRECTOR OF NUCLEAR ENERGY

The missions of the Nuclear Energy Division (DEN) were confirmed last March in the new decree defining the organisation and operation of the CEA: helping the French nuclear power industry to generate safe, competitive and sustainable energy.

More than ever focused on the societal issues of the 21st century, our research reflects the concerns voiced at the COP 21, the United Nations international conference on climate change held in Paris late 2015. A legally binding agreement setting out to keep global warming below 2°C was signed unanimously by all 195 countries that took part in the conference. Meeting this commitment necessarily involves reducing our use of fossil fuels and increasing the fraction of electricity in the energy mix. This means that we need to encourage the widespread use of carbon-free electricity for which nuclear energy represents one of the key solutions, together with renewable energy. Thanks to its nuclear industry, France is one of the European countries that emits the least CO_2 per kilowatt hour. Sometimes forgotten, it is this same industry that produces very little atmospheric pollution, which is an undeniable advantage from a public health perspective. Nuclear energy has also lent our country a significant competitive edge for several decades thanks to its relative energy independence.

In France, the Energy Transition for Green Growth Act dated 17 August 2015 is based on enhancing our energy efficiency and implementing a low-carbon energy mix in which nuclear energy and renewable energy play a complementary role.

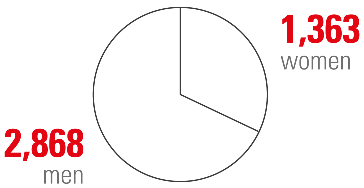
It is in this context that the Nuclear Energy Division is running its programmes. In 2015, we continued to support our industry partners in the field of reactors and the nuclear fuel cycle, focusing on major issues such as lifetime, competitiveness and nuclear safety in facilities. We also worked on the future generations of nuclear systems within a longer term perspective. We thus presented the government with a file detailing our results on the multiple recycling of spent fuel and the transmutation of long-lived radioactive elements in line with research on the new generations of reactors. Notable progress has also been made in our clean-up and dismantling projects. The commissioning of the Maestro remotely operated robot developed with our industrial partners is an unquestionable technical achievement: after having been launched on a first worksite in mid-2015, this robotic arm has been used for laser cutting operations in a highly irradiating environment since late 2015, which is a world first.

The most significant milestones achieved by the DEN teams whom I would like to thank for their professionalism and unstinting commitment, are detailed in this report. I hope you will enjoy reading about our recent activities.

KEY FIGURES

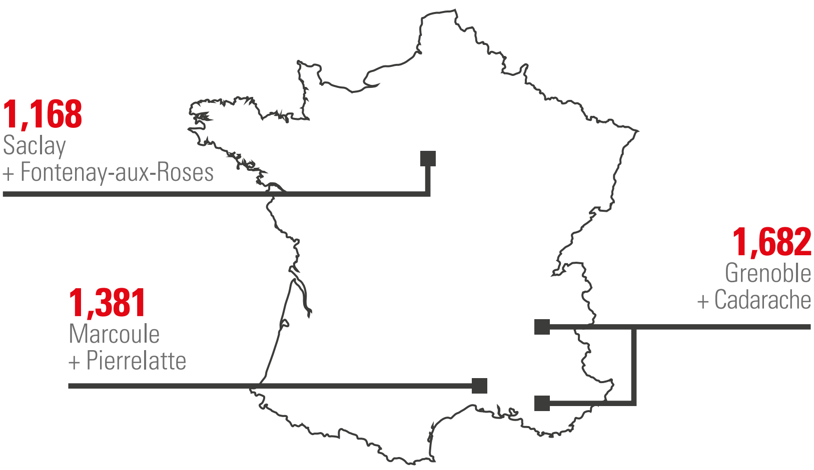
4,231 EMPLOYEES

including…



including…

spread over 5 centres



157
NEW HIRES

246
DOCTORAL CANDIDATES

36
POST-DOCTORAL RESEARCHERS

517
PUBLICATIONS

52
PATENTS FILED

FUTURE INDUSTRIAL NUCLEAR SYSTEMS

The Nuclear Energy Division (DEN) is currently working on the 4th generation of fast reactor systems for the future. Their development is needed to better meet requirements with respect to secure energy supplies and energy independence. These systems can optimise the material management process thanks to the possibility of better exploiting uranium resources, while enabling the multiple recycling of plutonium and minimising radwaste production. The options for the related future fuel cycle are also being investigated in coherence with studies led by the DEN on the Astrid project - an integrated technology demonstrator for the 4th generation of sodium-cooled fast reactors - of which the CEA is the project owner. This project is currently in its conceptual design phase.

MOX fuel.

FOCUS ON

REPORT ON THE SUSTAINABLE MANAGEMENT OF MATERIALS

Within the framework of the Act dated 28 June 2006, the CEA submitted a report to the French government on the progress made in research on separation & transmutation and the multiple recycling of plutonium in fast reactors. This document was prepared by the CEA, written in collaboration with EDF and AREVA, and includes contributions from the CNRS. The sections of this report cover in succession:

- The main principles underpinning research on 4th generation systems and especially their capacity to ensure the sustainable management of materials and waste, the various systems being studied, and the possible deployment scenarios for these systems in France;
- The results of research coordinated by the CEA on the multiple recycling of plutonium, as well as the separation and transmutation of long-lived radioactive elements;
- The proposed choices for the Astrid integrated technology demonstrator, a sodium-cooled fast reactor of which the CEA is the project owner.

BACK-END OF THE FUTURE FUEL CYCLE

In line with the Astrid reactor's design studies, the DEN is conducting research on the future fuel cycle. The aim of this research is to assess all the options related to the management of nuclear materials for the fast reactor fleet, in accordance with the provisions of the Act dated 28 June 2006 on the sustainable management of radioactive materials and waste.

MULTIPLE RECYCLING OF FUELS IN A FLEET INCLUDING FAST REACTORS

France has the industrial capacity to reprocess and recycle spent fuel from its current nuclear power fleet. The prospect of multiple recycling of materials in a fleet which includes 4th generation fast reactors requires adapting:

- The reprocessing technologies to make them suitable for the specific features of spent MOX[1] fuel from pressurised water reactors (PWRs) and fast reactors;
- The MOX fabrication technologies to make them suitable for the specific features of fast reactor fuels.

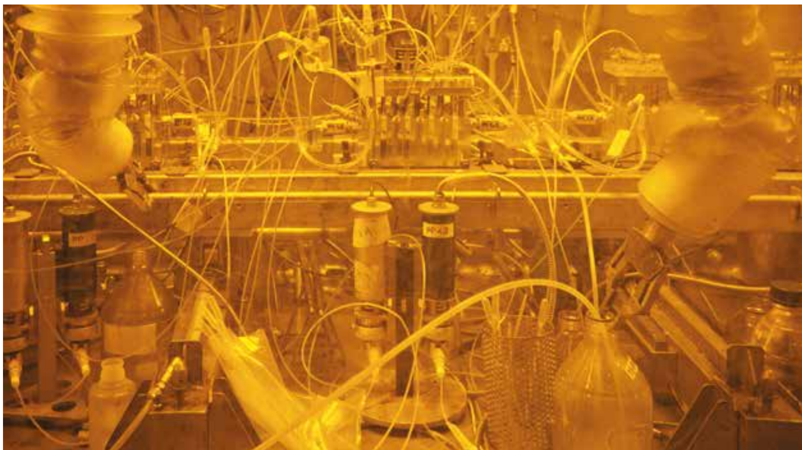
To address this second issue and following on from R&D tests performed in CEA laboratories, an initial campaign to manufacture 300 fast reactor pellets with an Astrid-based annular geometry was successfully carried out in 2015 in the Melox facility, in collaboration with AREVA. These initial, very encouraging, results will be consolidated by new campaigns to optimise the fabrication conditions.

STUDIES ON MINOR ACTINIDE SEPARATION AND TRANSMUTATION

Americium has been identified as the first target for a separation and transmutation strategy whose objective is to reduce the long-term radiotoxicity of ultimate waste and optimise its disposal by reducing heat transfers. Studies are focusing on the single-stage separation of americium only, downstream of the separation of uranium and plutonium. The demonstration of the EXAm[2] process, developed by the CEA and already tested at laboratory scale, is part of a more comprehensive experiment, called the "integral experiment". This involves carrying out the various phases of the process, from the dissolution of a spent fuel through to the fabrication of fuel pellets containing the americium resulting from the EXAm separation process. The aim is demonstrate the complete laboratory-scale recycling of americium using irradiated fuel. A key step was achieved in 2015 with the recovery of several grammes of americium from a raffinate of concentrated fission products.

(1) Mixture of uranium oxide and plutonium oxide.

(2) Extraction of americium.

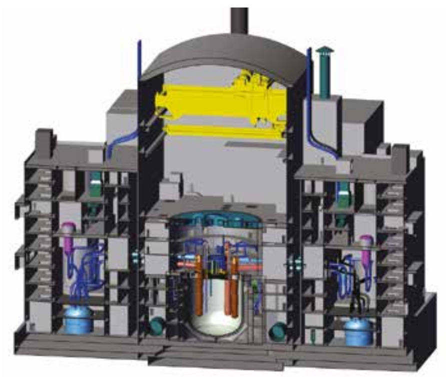


Atalante facility at Marcoule where the minor actinide separation tests are performed.

Mock-up of the Astrid hot pool.

4TH GENERATION REACTORS

The CEA is responsible on behalf of France for research on innovative nuclear systems - called 4th generation - which integrate major technological breakthroughs compared with the previous generations of reactors. For this reason, it is leading the design studies for an integrated technology demonstrator of a sodium-cooled fast reactor (SFR) called Astrid, while continuing its monitoring and R&D on all other relevant technologies for this 4th generation.



Cross-sectional view of the Astrid nuclear island.

Astrid is an integrated technology demonstrator that is designed to generate 600 MWe so as to demonstrate the 4th generation SFR technology on a pre-industrial scale, particularly in the fields of nuclear safety and operability.

PLATFORMS TO SUPPORT THE ASTRID DESIGN PHASE

The development and qualification of the Astrid technological options require a series of specific test means, some of which are in sodium while others are in water with respect to the simulating fluid. Sometimes, existing means need to be adapted to meet the Astrid project requirements, or new means are developed. A detailed analysis of the needs and existing means made it possible to deploy a test programme strategy based on four sets of experimental means.

- **The Papirus platform** comprises a set of experimental devices designed to simplify the use of sodium in future reactors, to optimise the operation of these reactors, to control their investment and operational costs, and to demonstrate their safety cases. The test means range from small glove boxes containing a few grams of sodium, up to test devices required to develop sodium-gas heat exchangers, to qualify sodium instrumentation (flowmeters, pressure sensors, etc.) or the electromagnetic pumps for Astrid. As part of its general safety approach, the Astrid project intends to use electromagnetic pumps to circulate the sodium in its secondary systems. These pumps not only reduce the risk of sodium leaks, but also improve the reactor's overall reliability and maintainability. To support their design process, the CEA is developing several numerical models to represent the physical phenomena occurring in this type of pump and a one-of-a-kind sodium test loop in Europe to validate these models, which is called PEMDYN[1]. Its main component is an electromagnetic pump. Five metres long and weighing 7.5 tonnes, this pump can provide a maximum sodium flow rate of 1,500 m³/h (on a 1/4 scale of the Astrid pumps). The first tests started in 2015 with the flow rate progressively being ramped up; the nominal flow rate of 1,500 m³/h will be reached sometime in 2016.
- **The Giseh platform** comprises a series of test means using simulating fluids. These means are used to meet nuclear steam supply system and core related needs in the fields of hydraulics, thermal-hydraulics and flow-induced vibration analysis. Water at around 50°C shows similarities with sodium (density, viscosity), which allows the research teams at the CEA to better understand these aspects. In 2015, a 1/6 scale mock-up of Astrid's hot pool was built and placed in water on a specific loop to conduct the first test campaigns needed in particular to assess the occurrence of gas entrainment on the surface of sodium. These tests will be continued to simulate the different operating conditions in the Astrid primary system and to help qualify the Cathare thermal-hydraulic code.
- **The Cheops platform** comprises a series of large sodium test loops designed for large-scale R&D programmes and component qualification. The design and construction studies launched in mid-2014 were continued in 2015 with a target commissioning date set for around 2020.

(1) A French abbreviation for dynamic electromagnetic pump.

Artist's impression of the Plinius-2 platform.

■ **The Plinius-2 platform,** which is set to replace the Plinius facility, will be devoted to studying severe accidents with respect to corium and its interactions. It will meet R&D requirements related to the experimental simulation of severe accidents for different reactor systems (using water or sodium as the coolant). In 2015, the building design and process studies were launched, focusing on the design of the corium melting furnace which will be required to melt a total of 500 kg of material.

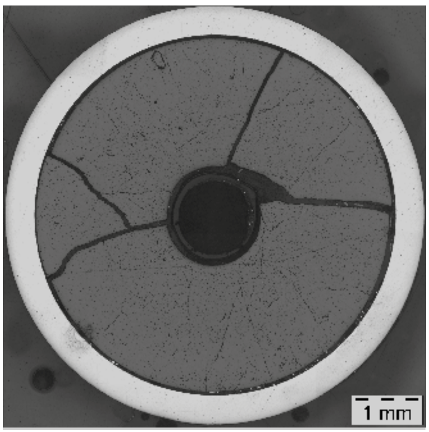
FOCUS ON

END OF THE ASTRID PRELIMINARY DESIGN PHASE

In December 2015, the CEA submitted a summary of the preliminary design studies and recommended safety options to the Astrid project monitoring committee composed of the relevant ministerial authorities. The conceptual design phase aimed at consolidating and finalising the main reactor design options choices and defining the safety options. The file submitted to the authorities is based on more than 2,000 engineering documents and highlights the potential of the Astrid design proposed for the next stage. After having examined the file, the committee agreed to launch the basic design phase which will run through to 2019. This phase will provide a preliminary definition of all the systems and components and the related substantiation programme (to be carried out in the subsequent phase), as well as a first draft of the preliminary safety report. The project is moving ahead according to the schedule defined with the ministerial authorities under the agreement signed between the government and the CEA under the future investments programme.

STUDIES ON PHÉNIX FUELS TO SUPPORT THE DEVELOPMENT OF ASTRID FUELS

The Astrid design is integrating experience feedback from all fast reactors having operated throughout the world. This is the case for the cladding materials, the sub-assembly structural materials, and the fuel material which is a mixed (U, Pu) O_2 oxide in a stack of fuel pellets with heterogeneous compositions. Objects irradiated in the Phénix reactor at the Marcoule centre have been identified as relevant for supplementing the qualification files for the Astrid core. Additional assessments were launched in 2013, followed by a programme in 2015 on fuel pins from an experimental sub-assembly with similar characteristics to the pins designed for the Astrid core. The objective is to supplement both the file on the reference cladding material for the first Astrid cores and the qualification process for the fuel behaviour code. In 2015, the pins and steel cladding sections were sent to the CEA laboratories at Cadarache and Saclay in preparation of the first examinations to characterise their post-irradiation behaviour. Studies on irradiated objects from Phénix will continue throughout the Astrid design phase to supplement the files justifying the lifetime of its components and qualifying its design codes.



Macrographic cross section of a pin from a Phénix fuel sub-assembly to support the Astrid component design and qualification process.

PARTNERS

Numerous industry partners have rallied round the CEA for the Astrid project and are contributing to the different reactor packages according to their expertise. Agreements signed with the Astrid partners require that some contributions to the project be self-financed. At the end of 2014, the Astrid project counted a total of 13 collaborations. CNIM joined the project in 2015 to provide a preliminary optimisation study of the gas power conversion system (PCS) efficiency.

Other partnerships cover specific R&D issues to support the project. In 2015, three agreements were signed; one with the Italian national agency for new technologies, energy and sustainable economic development (ENEA), and two with German organisations: Karlsruhe Institute of Technology (KIT), and the Helmholtz-Zentrum Dresden Rossendorf research laboratory (HZDR).

The new JANNuS platform ion accelerator at Saclay.

FUNDAMENTAL SCIENTIFIC AND TECHNOLOGICAL RESEARCH

Fundamental scientific and technological research focuses on activities that are upstream of applied research, by resolving cross-functional issues through other fields covered by the DEN. Driven by dynamic collaborations, especially on a national and European level, this research helps expand our database and improve the scientific quality of knowledge needed to establish the relevance of solutions recommended to solve the main issues of nuclear energy in three different areas: materials, fuels and separation chemistry.

OFFICIAL OPENING OF A NEW ION ACCELERATOR IN THE JANNuS FACILITY

The JANNuS facility provides the international scientific community and industry with a platform that is unique in Europe for irradiating materials by charged particle fluxes, in order to observe and quantify any microstructural changes. Over the past five years, progressive investment has enabled improvements to be made to its leading-edge equipment and instrumentation. In 2015, one of the three ion accelerators was replaced by a new state-of-the-art model. The improved reliability, and the more powerful I&C system of this new accelerator enable high quality irradiation to be carried out over long periods, with minimum supervision. The number of proposals in response to calls for projects on the platform has doubled in five years, and proposals for irradiation experiments have tripled.

SUCCESS OF THE SECOND MINOS WORKSHOP

The second international workshop of the MINOS centre of excellence for nuclear materials, organised by the DEN in association with the National Institute for Nuclear Science and Technology (INSTN) at Saclay, took place over three days in November at the INSTN at Cadarache. It addressed the effects of irradiation on materials used in the current reactor fleet or intended for the nuclear systems of the future or for fusion (mainly metal alloys and fuel materials), focusing on flux and dose effects. Material research plays a major role in providing answers to current and future nuclear issues (extending nuclear power plant service life and availability, increasing safety, optimising cladding materials and fuels, developing 4th generation nuclear systems, managing radioactive waste, etc.). Just over 140 experts in the fields of materials sciences and nuclear engineering attended this workshop, including thirty or so participants from Europe and abroad, indicating the scientific community's interest in this subject.

FIRST IRRADIATION CREEP EXPERIMENT USING MICROMACHINES

The mechanical behaviour of materials under irradiation is a major issue for the nuclear industry. This behaviour has been well characterised on a macroscopic scale. At microscopic scale, however, the deformation mechanisms under irradiation are still not well understood, in particular the irradiation creep of structural materials used in nuclear reactors (austenitic steels or zirconium alloys). In this context, the teams at the DEN and the *Université catholique de Louvain* have set up an original experiment. It involves combining charged-particle irradiation on the JANNuS irradiation platform and the MEMS (Microelectromechanical Systems) technology[1]. This experiment enabled the effect of ion irradiation on a mechanically-stressed material to be measured for the first time, thus opening up prospects for understanding irradiation creep in model metal materials.

(1) This is an extremely small mechanical system (a few mm^2), often built on silicon, with at least one micrometre-scale component. It acts as a sensor or an actuator.

Participants at the second MINOS workshop.

OPTIMISING THE CURRENT NUCLEAR INDUSTRY

The DEN is conducting research to address the challenges facing its industrial partners. The first objective is to support EDF in increasing the competitiveness of the French fleet currently in operation, with industrial implications in terms of reactor service life, performance, availability and safety. The second objective, in collaboration with AREVA and Andra, is to optimise or adapt the front-end and back-end facilities of the nuclear fuel cycle to meet current and future industrial challenges.

Experimental set-up for uranium extraction by supercritical CO_2.

FRONT-END OF THE CURRENT FUEL CYCLE

The front-end of the fuel cycle includes the industrial operations associated with uranium, from its mining through to its enrichment, for use in 2nd and 3rd generation reactors. Recent years have seen a reduction in ore grades and a need to refurbish existing facilities. The DEN is therefore working on improving performance levels in terms of the selective extraction of uranium, and its purification and conversion into a form of hexafluoride to achieve the required level of purity for uranium enrichment.

EXPLORATION AND MINING

In this field, AREVA uses one of the DEN's laboratories at Cadarache to estimate the sensitivity and accuracy of uranium measurements in boreholes. The teams have developed special modelling of the sensors used industrially by AREVA.

These models have been validated using measurements taken on calibration blocks belonging to AREVA at Bessines. Parametric studies have been used to investigate the sensitivity of the gamma counting rate to the actual uranium content of the soil, according to the different configurations encountered (geological formation characteristics, geometry of the borehole, presence of a casing, filling fluids, etc.).

This modelling will enable the teams to extend the range of validity and reduce the uncertainty associated with the correction factors applied to the gamma counting measurements used to establish uranium resources and reserves. Innovative approaches based on gamma spectrometry will also be studied in order to provide fast characterisation of any radioactive imbalance between uranium and its daughter products.

EXTRACTING URANIUM FROM CONVENTIONAL ORES

The DEN is studying an alternative uranium extraction process using supercritical CO_2 as the solvent. The expected improvements include the use of considerably less water, organic solvents and chemical reagents, and a reduction in the number of grinding stages due to the high diffusivity of supercritical CO_2. Extraction efficiencies of around 97% have been obtained at laboratory scale, enabling the preliminary design of an extraction workshop and providing the basis for a technical and economic study of this process. The envisaged prospects are improved selectivity of the process and its pilot-scale demonstration.

CONVERSION: PURIFICATION OF URANIUM-BEARING SOLUTIONS

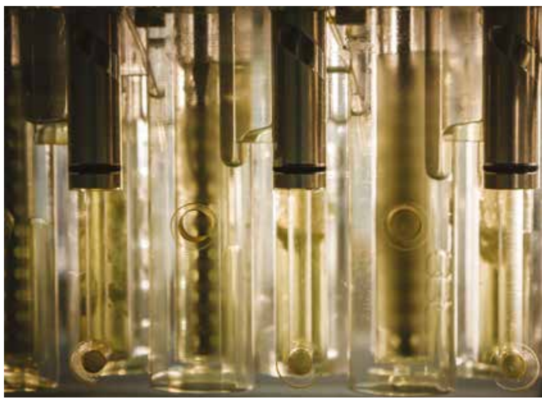
AREVA has solutions and effluents containing a high level of natural uranium which can be re-used as long as they are decontaminated beforehand to remove any traces of radioelements so that they are compatible with processing at the Comurhex plant. To do this, the DEN has proposed testing the extractive and selective properties of a monoamide molecule. The objective is to have a process with very high decontamination factors for the selective extraction of uranium in order to remove radiological impurities, in the presence of large quantities of chemical impurities.

In 2015, the final process configurations were calculated and a test campaign was conducted in the DEN's facilities, firstly on a synthetic solution, then on the real solution supplied by AREVA. The analyses confirmed the feasibility of the process and its performance levels in continuous operation at laboratory scale. The objective now is to design and cost the industrial-scale process.

ISOTOPE SEPARATION

In the field of isotope separation, the DEN is conducting an active technology watch on uranium enrichment processes, in order to maintain the CEA's expertise in this strategic area. It is working in particular on the Silex process (Separation of Isotopes by Laser EXcitation), for which it is carrying out studies which should contribute to the assessment of the performance levels of this process.

Test campaign on a set of mixer-settlers to validate a selective uranium extraction process.



Plasma furnace used for incineration tests
to support the development of the Pivic process.

BACK-END OF THE CURRENT FUEL CYCLE

Programmes are being conducted to support AREVA in order to optimise or adapt the processes for spent fuel reprocessing at the La Hague plant and for MOX fuel fabrication at the Melox plant. They are also designed to support Andra so as to provide the scientific and technical information needed for the Cigéo waste acceptance files (Cigéo, LL-LLW). Lastly, such programmes set out to guide EDF in its management of certain types of waste, including that from the dismantling of natural uranium graphite gas (UNGG) reactors.

PROGRESS ON THE PIVIC PROCESS

The Pivic in-can incineration-vitrification process, developed by the DEN in the joint vitrification laboratory, in partnership with AREVA and Andra in the context of the French future investments programme, is designed to treat and condition alpha-contaminated mixed soft housekeeping waste[1] (both organic and metal) generated by the activities of the Melox and La Hague plants. In 2015, the initial validation of a solution designed to limit the clogging of the waste incineration reactor was carried out. Incinerating this waste causes potential clogging of the walls of the reactor, which could have a major impact on the rate at which the waste is treated industrially. One solution being studied consists of confining the waste to be treated in a fibreglass sack, which also acts as a filter, retaining the solid residues (ashes and radionuclides) from the incineration of the organic part of the waste. To quantify the capacity of the sack to retain the contaminant, a campaign of incineration tests was carried out with a product simulating plutonium oxide. An average retention rate of 95% was recorded, the mass of deposits being less than 1% of the mass of contaminant introduced, and the remaining 4% being retained on the gas treatment equipment. These values show the efficiency of the fibreglass sack in retaining the radionuclides and thus reducing the clogging of the reactor walls, and therefore confirm the potential of the process with regard to the proposed industrial treatment rate. The results will now be consolidated by continuing the study using other products simulating plutonium oxide and other types of sack.

SUPPORTING ANDRA

In the context of the French Act of 28 June 2006 on the sustainable management of radioactive materials and waste, the DEN is supporting the deep geological repository project (Cigéo), of which Andra is the project owner. A code that describes the evolution of a passive layer[2] on the low alloy steels being considered for disposal, and which is therefore used to simulate their corrosion over the very long term, has been submitted to, and accepted by the Agence pour la Protection des Programmes (French software protection agency). This code, called Calipso, jointly developed by the CEA and Andra, uses numerical methods for solving the equations in a model describing the evolution of the passive layer. It can, for example, simulate the evolution over time of the position of the passive layer in physical space associated with the environment. To improve its prediction capability, the Calipso code must be coupled with a transport geochemistry code. Calipso can calculate the fluxes exchanged with the environment according to the chemistry imposed by the latter, whereas the geochemistry code calculates the evolution of the chemical speciation caused by the corrosion of the steel and therefore transmits a new chemistry to Calipso. This code coupling process must enable simulation of the corrosion of steel over the very long term, around a thousand years.

Experimental device for confirming the dissolution kinetics
of a layer of iron oxide, a phenomenon simulated by the Calipso code.

(1) Also called "mixed technological waste".

(2) Chemical barrier capable of slowing down the corrosion phenomenon of the underlying material.

Experimental facility on the Plinius platform at Cadarache for observing the formation of a debris bed during a corium-water interaction test, using X-ray imaging.

2ND AND 3RD GENERATION REACTORS

The CEA is conducting research to support current 2nd generation French pressurised water reactors (PWRs) and the deployment of 3rd generation reactors. Research is principally carried out with EDF, AREVA and the IRSN, and addresses the industrial issues of improving the performance, extending the service life and increasing the safety level of nuclear power plants.

STUDIES OF SEVERE ACCIDENTS

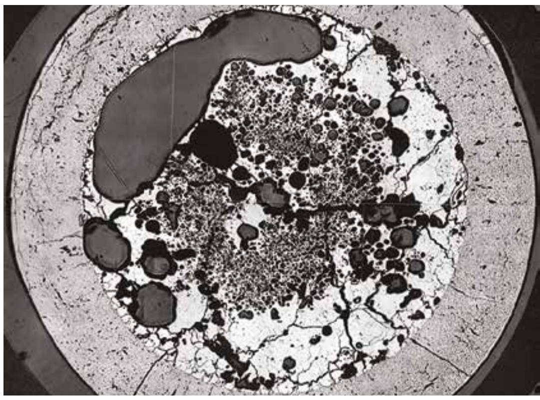
Although the Fukushima-Daiichi nuclear accident did not reveal any major shortcomings in terms of knowledge and R&D objectives, it did underline the need to continue with the R&D programmes focussing on enhancing the robustness of the mitigation solutions proposed for both 2nd generation reactors and new 3rd generation concepts. The credibility of this R&D is based largely on our ability to maintain high-performance experimental facilities.

X-RAY IMAGING OF THE FORMATION OF A DEBRIS BED DURING A CORIUM-WATER INTERACTION TEST

When a severe accident occurs in a nuclear reactor, the melting core materials (corium) may come into contact with water and interact explosively. This is the subject being studied in the "corium-water interaction" project, chosen by the French national research agency in the context of a call for "nuclear safety and radiation protection research" projects as part of the French future investments programme. The first test of this project, conducted jointly by the IRSN, the CEA and the University of Lorraine, with the support of EDF and AREVA, was successfully carried out in a facility on the DEN's Plinius platform at Cadarache. Using X-ray imaging it monitored the fragmentation and dispersion of a corium jet over 2/3 of the water height, and the composition of the debris bed, its temperature and associated boiling. The objective of the experiment is to obtain quantities comparable to those produced by the computer codes used to simulate these interactions. The comparison of the simulation and the experiment will enable the validation file of these codes be substantiated.

SUCCESS OF THE 5TH VERDON TEST

At the Verdon facility at Cadarache, the DEN is conducting a programme to improve knowledge of the behaviour of fission products during an accident in a PWR. The Verdon-5 test was conducted on 19 November 2015 in a new international context with EDF, ENGIE, US-NRC[1], JAEA[2] and the IRSN. It follows on from the first four Verdon tests conducted as part of the International Source Term Programme (ISTP). The objective of the Verdon-5 test, carried out using a high burn-up uranium oxide fuel, was to study the impact of boron on the chemical forms of iodine, then the effect of air ingress (perforation of the vessel or an "open vessel" accident) on the release of fission products, in particular ruthenium. The fuel sample, initially irradiated in an EDF reactor, was re-irradiated in the Osiris research reactor at Saclay in order to re-establish its short-lived fission product inventory (in particular iodine 131), and then taken to Cadarache. In addition to the numerous on-line measurements, quantitative measurements of the fission products deposited on the various components of the experimental system were taken after dismantling.



Verdon facility at Cadarache, for studying the behaviour of fission products during a severe accident (top). Molten fuel sample after a typical test in Verdon (bottom).

(1) United States Nuclear Regulatory Commission.

(2) Japanese Atomic Energy Agency.

(3) Physical Vapour Deposition – High Power Impulse Magnetron Sputtering.

EDF Cruas-Meysse nuclear power plant (900 MWe series).

EXTENDING THE SERVICE LIFE OF THE FLEET'S REACTORS

The objective of the Fluole 2 experimental programme, started in 2014 by the DEN and co-funded by EDF, is to contribute to the validation of the dosimetry interpretation model of the irradiation monitoring programme (PSI) for the French fleet of nuclear power reactors. It follows on from the Fluole programme, carried out from 2006 to 2007, representing the 1,300 MWe series. Fluole 2 is an integral experiment representing the 900 MWe and 1,450 MWe PWR series, designed to supplement the qualification of the computational schemes for neutron propagation from the core up to the PSI capsules, to the vessel and beyond the vessel. The experiments are being carried out over three years, from 2014 to 2016, in the Eole reactor at Cadarache. Their aim is to qualify the computational schemes for various core configurations. The experimental results have shown that these schemes have a good predictive capability. The programme will therefore end in 2016 with another core configuration.

FUELS

DEVELOPMENT OF INNOVATIVE FUEL CLADDING WITH IMPROVED RESISTANCE TO OXIDATION

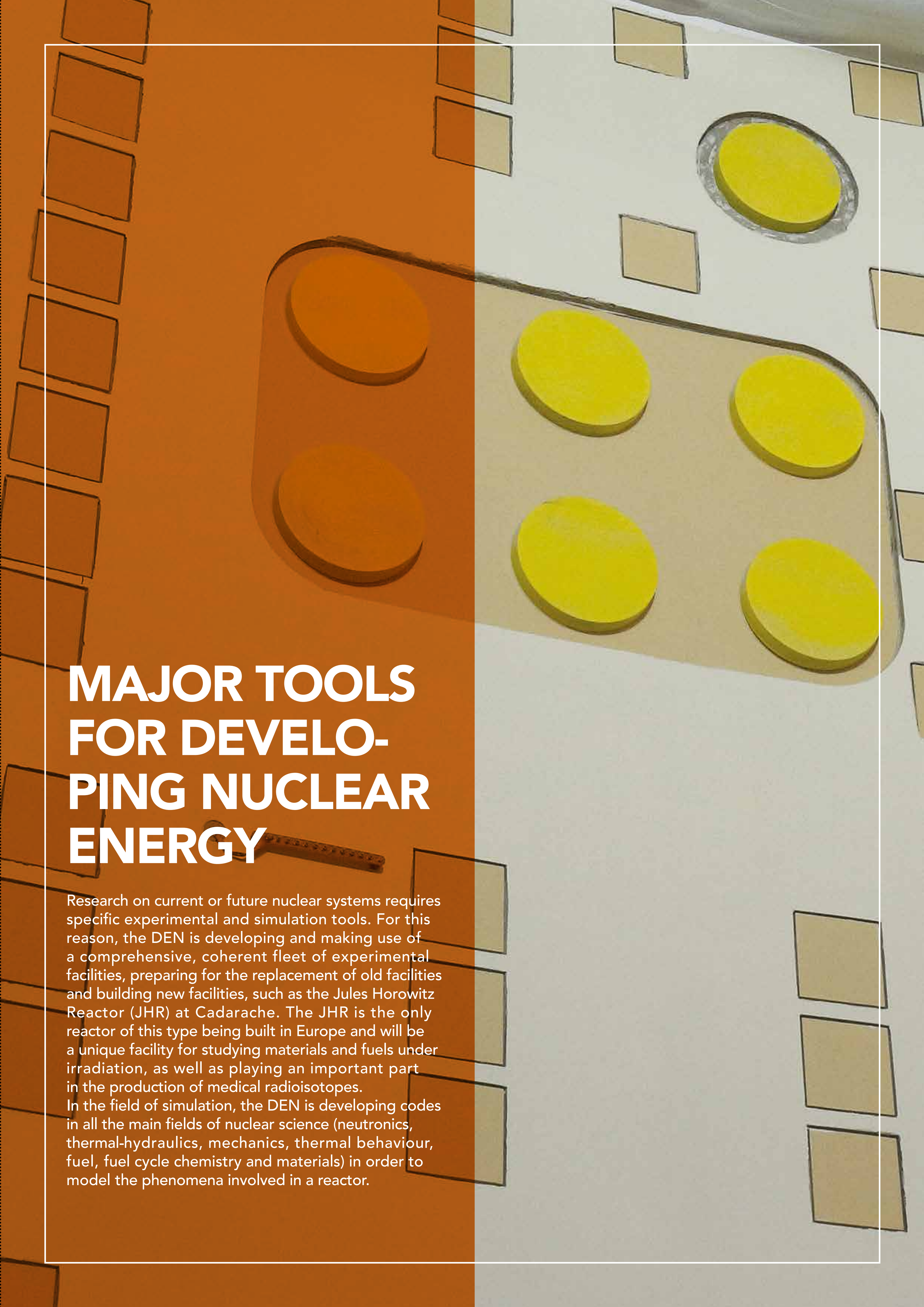
The DEN is working with its partners of the tripartite institute (CEA/EDF/AREVA) on the development of innovative solutions for fuel cladding, with the aim of improving its ability to withstand accident conditions, while maintaining a potential benefit in terms of its behaviour under nominal conditions. This is the EATF "Enhanced Accident Tolerant Fuel" concept.

- The first part involves the development of fuel cladding coated with chromium using a PVD-HIPIMS[3] hybrid process, which led to a CEA patent. Developed by the CEA in the context of the CEA - Belfort-Montbéliard technology university joint research laboratory, this coated cladding shows significantly improved resistance to oxidation, both in nominal conditions and in accident conditions at high steam temperatures. Its resistance to hydriding, the potential embrittling effects of which are known, is also improved. Tests have also confirmed the robustness of the coating obtained, for which the manufacturing process is currently at a pre-industrial stage. Studies will continue in 2016 with a view to industrial development in order to produce fuel rods more than four metres long (the fabrication of 50 cm sections is currently possible), enabling the fabrication of the experimental fuel rods chosen for irradiation in the context of the Halden Reactor Project international programme, under the auspices of the OECD's Nuclear Energy Agency.
- The second part, which has a longer term perspective, involves the use of cladding made of a silicon carbide composite (SiC/SiC) as an "EATF" solution. This composite was initially developed for gas-cooled fast reactors (CEA patents). This concept of multi-layer cladding with an internal metal liner makes it possible to envisage cladding that is leaktight during operation and provides improved resistance in accident conditions. The initial assessments carried out in situations representative of water reactors confirmed the benefit of continuing work to assess the performance more systematically and to look for ways of optimising the concept. They also removed reservations concerning maintaining leaktightness and resistance to recession (loss of matter) in aqueous environment.

Furnace used for analysing the behaviour of irradiated fuel during an accident transient.

ASSESSMENT OF THE IMPACT OF ACCIDENT TRANSIENTS ON THE BEHAVIOUR OF IRRADIATED FUELS

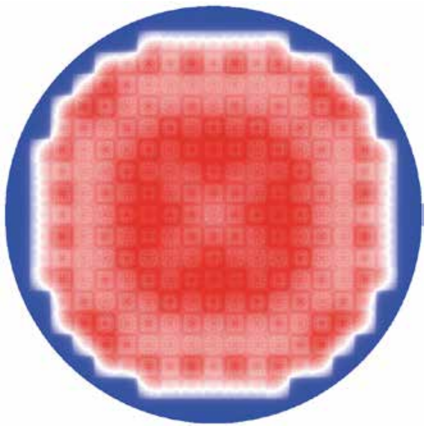
Analysing the impact of the conditions encountered during accident transients (loss-of-coolant accident, reactivity-initiated accident, etc.) on irradiated nuclear fuel is a central issue for proving the safety of reactors, and is the subject of several international programmes. The CEA has set up an original facility, Mexiico, to carry out analytical studies of the thermal and mechanical behaviour of irradiated fuel pellets under controlled temperature and confinement pressure conditions, representing those that may be found at the core of the fuel material in real accident conditions. An initial test on an irradiated high burn-up uranium dioxide pellet was successfully carried out in the context of the Nuclear Fuel Industry Research (NFIR) international programme, in accordance with the chosen protocol: pressurisation of the sample to 600 bar, temperature increase (60°C/min) up to 1,200°C, then gradual depressurisation while maintaining the temperature at 1,200°C, with on-line measurement of the gases released during the entire sequence. The tests will continue in order to determine the pressure threshold for which the release of fission gases (following the mechanical and thermal transformation of the fuel affected) becomes significant.



MAJOR TOOLS FOR DEVELOPING NUCLEAR ENERGY

Research on current or future nuclear systems requires specific experimental and simulation tools. For this reason, the DEN is developing and making use of a comprehensive, coherent fleet of experimental facilities, preparing for the replacement of old facilities and building new facilities, such as the Jules Horowitz Reactor (JHR) at Cadarache. The JHR is the only reactor of this type being built in Europe and will be a unique facility for studying materials and fuels under irradiation, as well as playing an important part in the production of medical radioisotopes.

In the field of simulation, the DEN is developing codes in all the main fields of nuclear science (neutronics, thermal-hydraulics, mechanics, thermal behaviour, fuel, fuel cycle chemistry and materials) in order to model the phenomena involved in a reactor.



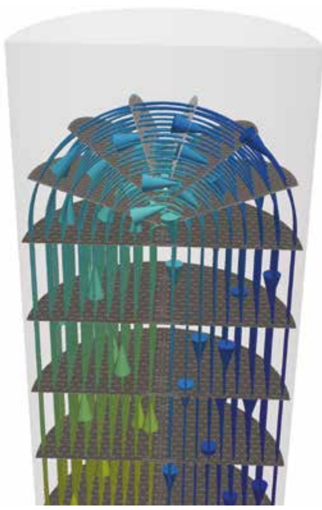
Neutronics:
2D fast flow distribution
of a large PWR core.

NUMERICAL SIMULATION

The DEN is developing software platforms and simulation codes in all the main fields of nuclear energy (neutronics, thermal-hydraulics, mechanical and thermal behaviour, fuel, fuel cycle chemistry and materials) to model the complex phenomena that occur in normal or accident operation of a reactor or a nuclear facility. Most of the codes developed by the DEN are used by the French nuclear industry. They have been distributed to international R&D organisations, mainly accompanying collaborations, under a large number of licensing agreements.

NEUTRONICS: DELIVERY OF VERSION 1.2 OF THE APOLLO3® CODE

The Apollo neutronics codes were developed at the CEA several decades ago and constitute a benchmark for pressurised water reactors (PWRs). One of the objectives of Apollo3® is to be usable for all types of systems: fast reactors as well as PWRs. Another code objective is to establish innovative computational schemes, removing the simplifying assumptions inherent in the second generation codes and providing access to more accurate results, with the aim of eventually being able to process a reactor core in a single computing step, as against the current two. Version 1.2, delivered to EDF and AREVA at the end of December 2015, is used to simulate initial industrial applications, subject to its integration in an environment or a computational system belonging to the partners. It was delivered with a set of test examples and acceptance test examples covering core and assembly calculations for PWRs and fast reactors. Modelling and neutronics simulation of the Astrid enhanced safety core (known as the CFV) have been carried out, demonstrating the ability of Apollo3® to handle the very heterogeneous geometries of this core in a more realistic way. In 2016, the industrial partners will have the opportunity to test the potential of the code and the degree of industrialisation of its new functions.



Thermal-hydraulics: display of the circulation of the primary fluid and its temperature in the tubes running through the technological components of the steam generator.

CRITICALITY SAFETY: DELIVERY OF THE CRISTAL V2.0 CODE PACKAGE

Cristal is the benchmark code package in France for the prevention of the risk of criticality in the fields of nuclear fuel cycle facilities and the transport of fissile materials. The new V2.0 version, delivered to the organisations that were involved in its development and qualification (the DEN, the IRSN and AREVA NC), incorporates the latest versions of the DEN's neutronics codes, together with recent, consistent libraries of nuclear data, and improved user interface, computational schemes and computing tools, specifically developed for the various criticality safety application areas. These enhancements have led to a significant decrease in discrepancies between calculations and experimental results, and better incorporation of the "burn-up credit"[1] in criticality safety studies for a very wide range of configurations representing the environments, geometries and spectra encountered in fuel cycle operations.

THERMAL-HYDRAULICS: DELIVERY OF VERSION V1.1 OF GENEPI+

Genepi+ is a new generation software application for the three-dimensional simulation of flows and heat exchanges in steam generators. Its V1.2 industrial version, scheduled for 2016, will replace the Genepi2 code currently in industrial use at AREVA NP for the design and safety studies of its generators. Its development required a V1.1 industrial pre-release version. Delivered to AREVA NP at the end of 2015, this version is aimed to prepare for the change of tool in its computational system for assessing vibration risks in steam generator tubes. This delivery constitutes an important milestone in the project, confirming the relevance and operational character of these new technologies to meet the industrial requirements of AREVA NP.

(1) Negative reactivity of irradiated fuel in comparison with new fuel.

JULES HOROWITZ REACTOR (JHR)

The construction of the JHR at Cadarache represents a major project for the CEA. The JHR is the only reactor of this type being built in Europe. It will provide a unique tool for studying materials and fuels under irradiation to support current and future nuclear reactors. It will also be used to produce a sizeable fraction of the radioisotopes needed for medical purposes. The JHR project is funded via the French future investments programme and is being built within the scope of an international consortium, with the CEA as project owner, nuclear operator and contracting authority of the facility.

FOCUS ON

CONCRETING OF THE REACTOR BUILDING DOME

The reactor building dome was successfully concreted in early 2015. The teams from Razel-Bec (civil engineering), AREVA (prime contractor) and the CEA were all involved. For the first time in France, this structure was poured in a single operation, which was possible by using an extremely fluid, self-compacting concrete that flows into position in the formwork by the force of its own weight.

PHOTO GALLERY 2015, THE YEAR'S CONSTRUCTION AND FACTORY WORK

JHR construction continued throughout 2015, with the project's electromechanical work progressively gathering pace and civil engineering moving ahead since the completion of the reactor building. The following construction site milestones are worth citing:

- Concreting of the reactor building dome;
- Pre-stressing of the reactor building containment; *Photo 1*
- Ongoing assembly of the hot cells in the nuclear auxiliary building; *Photo 2*
- Start of pool assembly operations;

Other project milestones include:

- Launching the manufacturing of the reactor block's first large components; *Photo 3*
- Earthquake-resistance tests to qualify the back-up generators. *Photo 4*

JHR EXPERIMENTAL CAPACITIES SERVING THE ICERR LABEL

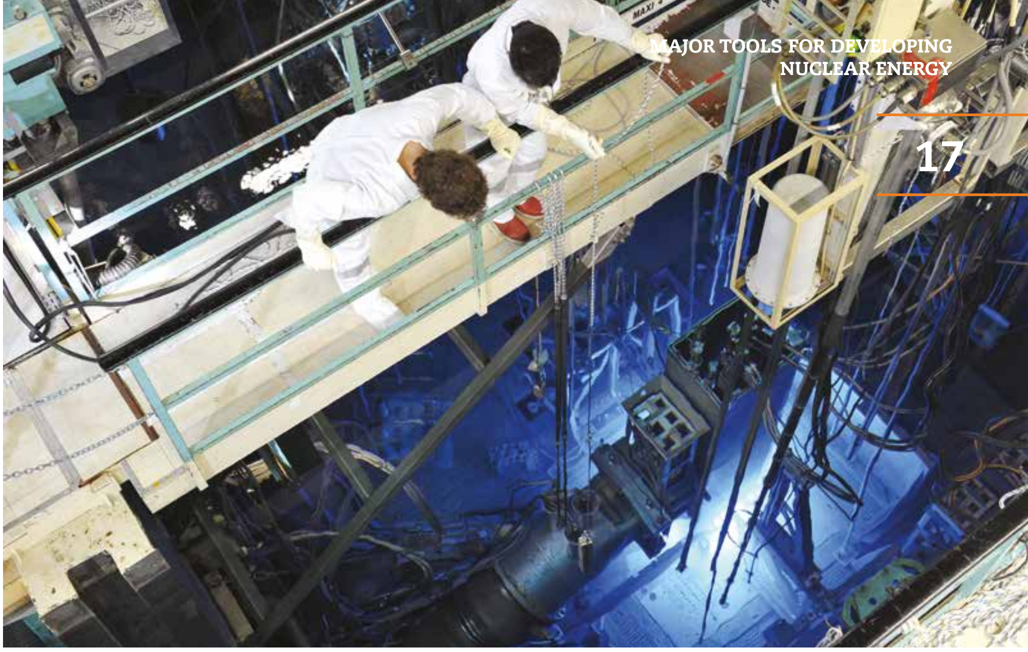
The International Atomic Energy Agency (IAEA) awarded its new label called ICERR - International Centre based on Research Reactors - for the first time to the CEA Saclay and Cadarache centres following their application relative to the JHR and its related research facilities (critical mock-ups, hot laboratories, etc.). Numerous experimental tools - including the JHR - will be made available to organisations of the IAEA member States for training and joint R&D projects development.


1


2


3

4



The Osiris research reactor at Saclay.

MAJOR FACILITIES SUPPORTING THE PROGRAMMES

The DEN uses major facilities to carry out its programmes. Securing this capacity is available involves operating, maintaining and ensuring the continuation of these major facilities (reactors, hot laboratories, etc.), optimising their experimental capacity or even creating or refurbishing facilities to adapt them for changing programmes or to meet regulatory requirements.

FINAL SHUTDOWN OF THE OSIRIS REACTOR

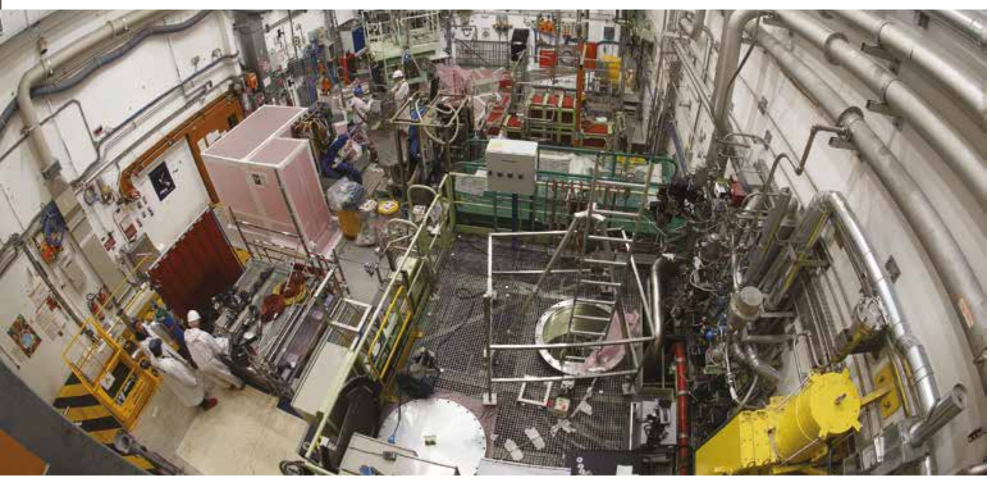
Osiris, an open core pool-type light water research reactor, was permanently shut down on 16 December 2015. Commissioned in 1966 at the CEA's Saclay centre, Osiris was used for almost 50 years for studying materials and fuels for current and future nuclear power plants. It also produced radioelements for medical and industrial applications as well as doped silicon for the electronics industry.

In 2015, prior to the final shutdown of the reactor, the teams performed 100 irradiation experiments (54 in 2014), honouring commitments that had been made. These experiments included supporting EDF's studies on extending the service life of the current fleet and improving the operability of reactors, and also, within the context of the CEA's programmes, the transmutation of minor actinides. The responsiveness and motivation of the teams also enabled a great many uranium target irradiation experiments to be carried out for the production of radioelements for medical use, to deal with the prolonged shutdown (almost three months) of the Dutch HFR reactor, the main supplier of these radioelements in Europe.

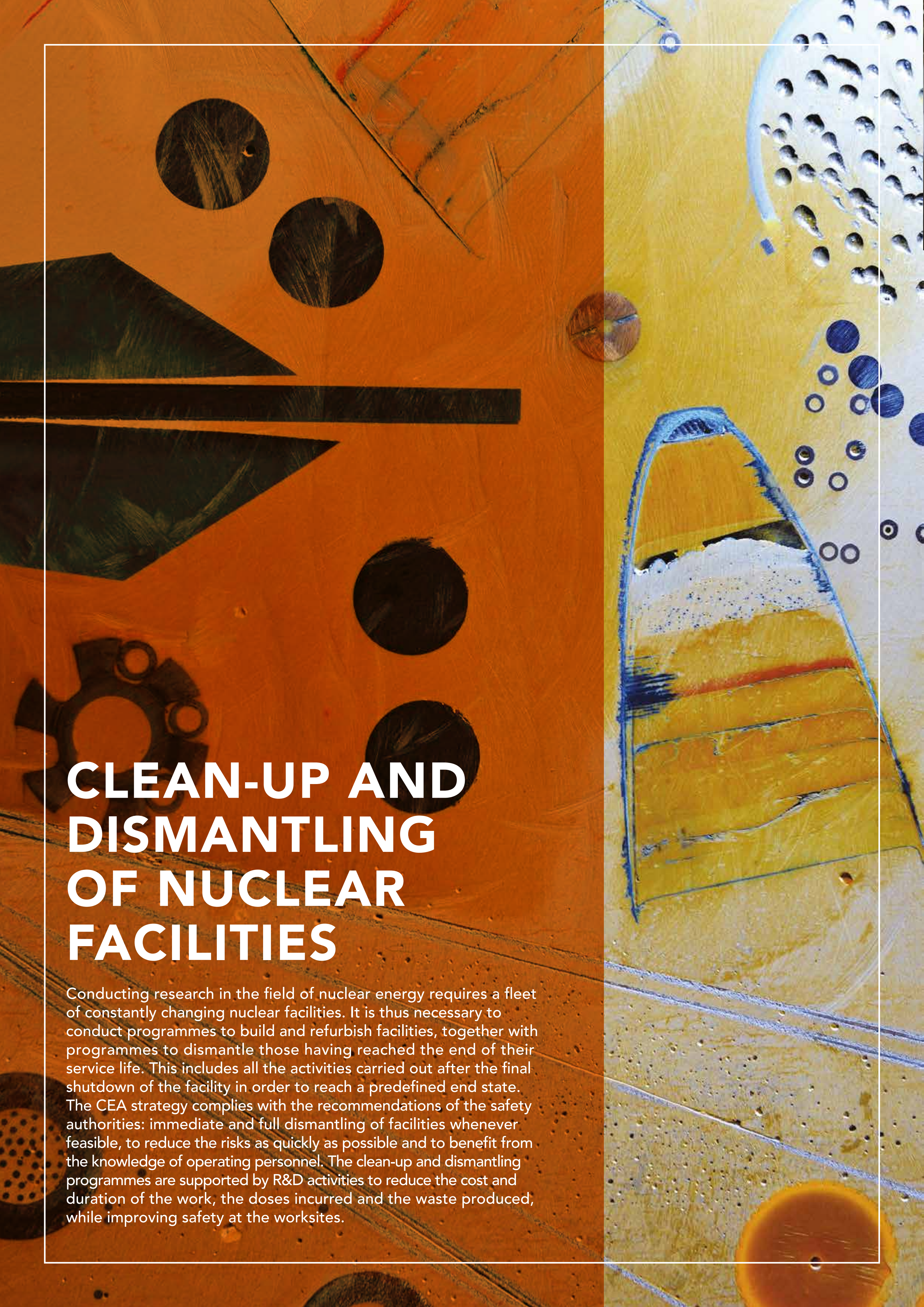
DIVERGENCE OF THE CABRI RESEARCH REACTOR IN PRESSURISED WATER LOOP CONFIGURATION

The Cabri research reactor at Cadarache, designed for carrying out fuel safety tests, went critical for the first time in pressurised water loop configuration on 20 October 2015. This new configuration will enable more representative tests to be performed on the fuel elements of the current fleet's pressurised water reactors (PWRs) in accident conditions. This divergence, authorised by the French Nuclear Safety Authority on 19 October, follows a major refurbishment programme to modify the facility for the French Institute for Radiation Protection and Nuclear Safety (IRSN) in the context of the continuation of the CABRI International Programme (CIP)[1] tests. The refurbishment involved the replacement of the Cabri reactor's sodium loop – used to reproduce the operating conditions of sodium-cooled fast reactors – by a pressurised water loop, as well as other renovation work needed to keep it operational. This work mainly involved strengthening the facility to enhance its earthquake resistance, improving its handling equipment, ventilation and fire resistance and also enabling "cold" tests of the pressurised water loop. The CEA is responsible for upgrading and refurbishing the facility. As the IRSN requested the experimental pro-gramme and will be both managing and conducting the experiments, it is providing the funding.

(1) Managed and co-funded by the IRSN, the objective of the CIP is to study the behaviour of nuclear fuel rods and their cladding during reactivity insertion accidents (RIAs) in PWRs. This programme, which was started in 2000 under the auspices of the OECD NEA, brings together numerous French and international partners.



General view of the Cabri reactor hall, at the end of the refurbishment phase.



CLEAN-UP AND DISMANTLING OF NUCLEAR FACILITIES

Conducting research in the field of nuclear energy requires a fleet of constantly changing nuclear facilities. It is thus necessary to conduct programmes to build and refurbish facilities, together with programmes to dismantle those having reached the end of their service life. This includes all the activities carried out after the final shutdown of the facility in order to reach a predefined end state. The CEA strategy complies with the recommendations of the safety authorities: immediate and full dismantling of facilities whenever feasible, to reduce the risks as quickly as possible and to benefit from the knowledge of operating personnel. The clean-up and dismantling programmes are supported by R&D activities to reduce the cost and duration of the work, the doses incurred and the waste produced, while improving safety at the worksites.

First cutting operation on a dissolution tank pipe using the Maestro arm equipped with a laser head (left: before cutting - right: after cutting).

As part of its INB inspection responsibilities, the nuclear safety authorities sent a joint letter in July 2015 asking the CEA to reassess its overall dismantling strategy, together with its material and radwaste management strategy. They also asked that operations be prioritised, the organisation and teams be strengthened, and the relevance of financial resources devoted to dismantling be analysed. This work will continue through to late 2016 at the end of which the CEA will propose a set of priorities, scenarios and schedules for the operations, with the objective of reducing risks associated with the source term.

CLEAN-UP AND DISMANTLING PROJECTS

There are currently 22 civilian regulated nuclear facilities (INB) undergoing a dismantling process at the CEA. The broad range of facilities to be dismantled - research or experimental reactors, laboratories, fuel cycle workshops & plant, waste treatment & storage facilities, etc. - means that the CEA cannot benefit from standardised or reproducible operations. Over the years, the CEA has gained significant experience, both in project ownership and in the methodologies and expertise required for the implementation of such clean-up and dismantling projects.

MARCOULE

There are several major dismantling worksites at the Marcoule centre, with three key projects underway: 1) dismantling of the UP1 spent fuel reprocessing plant, 2) dismantling of the Marcoule pilot unit (APM), and 3) preparation to dismantle the Phénix reactor which was shut down in 2009.

Long-lived intermediate-level waste drums placed in the interim storage area of the MAR 400 facility.

DISMANTLING THE UP1 PLANT

The UP1 plant reprocessed spent fuel from the G1, G2 and G3 nuclear reactors at the Marcoule centre with the goal of producing plutonium for French defence purposes. It also reprocessed civilian spent fuel from EDF natural uranium graphite gas (UNGG) reactors and from the Vandellos nuclear power plant in Spain.

This site is currently one of the largest dismantling projects underway in Europe. The dismantling programme covers the decladding workshops, the reprocessing plant itself, the Marcoule vitrification workshop (AVM), the support and interim storage workshops (ASE) and the retrieval and conditioning (RCD[1]) of legacy waste (bituminised and non-bituminised waste).

- On the plant side, 2015 was marked by the removal from storage and transfer of long-lived intermediate-level legacy waste from the MAR 200 workshop to the MAR 400 facility which meets the new earthquake resistance standards. This transfer was a major safety milestone for the French nuclear safety authority (ASN). It comprised a series of operations (radiological checks of drums, conditioning in containers, transport between two facilities, unloading, additional radiological checks and interim storage in the new area) that took place between May and December 2015. A total of 100 drums were transferred in 28 transport operations.

The Maestro remotely operated arm was used in an active environment in the plant late 2015 to perform laser cutting operations on the dissolution tanks in which spent fuels used to be dissolved as part of their treatment. A world first was achieved when the arm was coupled with a laser technology, there by providing an appropriate solution for cutting very strong, thick (several centimetres) stainless steel structures in a harsh environment: high level of radioactivity, large tank sizes and weights, poor accessibility, and working remotely or in «blind» conditions. The goal is to finish dismantling the first dissolver in late 2016 and the second in late 2018.

(1) RCD: a French abbreviation for Reprise et Conditionnement des Déchets.

Cutting a centrifuge using the Maestro arm in a hot cell of the Marcoule pilot workshop.

- Concerning the Marcoule vitrification workshop (AVM), the dismantling studies were launched and reinforcement work on the facility was started as requested by the ASN following the complementary safety assessments (stress tests) performed in wake of the Fukushima accident. For this reason, phase 1 of the dismantling work on the top part of the evaporator was finalised in 2015. Phase 2 is expected to be launched in 2016.
- As regards the support and interim storage workshops (ASE), dismantling is expected to take place as the facilities are progressively shut down. In 2015, preparatory work was started in order to drain the ponds not used at the liquid effluent treatment plant (STEL) at Marcoule, with this work set to continue through 2016.
- There are two main categories of operations in the field of legacy waste retrieval and conditioning (RCD): the retrieval of drums containing bituminised waste, and the retrieval of non-bituminised waste. For the first category, the recovery of bituminised waste drums from shielded cubicles 1 and 2 in the liquid effluent treatment plant is continuing in line with ASN expectations. For the second category, this involves characterising other legacy waste, to be recovered by 2030, which is currently stored in decladding pits and in the north area pits, e.g. metal structural waste such as magnesium, aluminium or steel, and powdered waste such as resins, zeolite or sludge.

DISMANTLING THE MARCOULE PILOT WORKSHOP (APM)

Commissioned in 1962 and shut down in 1997, the APM was built to validate the lab-developed irradiated fuel reprocessing processes on a pilot-scale. This facility comprises 30 hot cells, 5 shielded lines and 230 glove boxes. Since mid-2015, the Maestro robotic arm has been used to perform dismantling operations by mechanically cutting up the different process equipment and removing the resulting waste. Late 2015, Maestro had removed and cut up two centrifuges, a pH meter, a pulse filter, a settling tank and various pipes, thus representing about 1 tonne of waste which will be transferred to the Andra disposal facility in the Aube department. This pilot worksite will continue in 2016 and an operating experience report will be sent mid-year to the nuclear defence safety authority.

DISMANTLING THE PHÉNIX PLANT

The Phénix sodium-cooled fast reactor was shut down in late 2009. Pending the publication of the decree authorising dismantling which is expected sometime in 2016, the preparatory work was continued throughout 2015.

In this area, it is worth citing the carbonation of one of the secondary systems of the reactor. These systems have been drained since 2011 but the presence of a film of residual sodium on the pipes required a two-phase treatment involving carbonation and rinsing. Approved by the ASN, the carbonation of the first system was successfully performed in 2015. This involved circulating a controlled mixture of steam, carbon dioxide and nitrogen to transform the residual sodium first into hydrated sodium hydroxide (soda) and then into chemically inert carbonate. Preparatory operations will then be carried out on this system before it can be rinsed in 2017.

At the same time, the construction of the NOAH facility designed to transform sodium liquid from the reactor into soda also continued in 2015. The basemat concrete was poured in August, which marked a key milestone in the construction of this facility.

FONTENAY-AUX-ROSES

The clean-up and dismantling activities at the Fontenay-aux-Roses centre concern two regulated nuclear facilities (INBs): process INB 165 and support INB 166. The first facility comprises all the buildings in which R&D programmes were conducted in the field of radiochemistry and spent fuel reprocessing. The second concerns all the other facilities, in particular those used for waste management.

SUBMISSION OF THE FILE REQUESTING AUTHORISATION FROM THE ASN TO MODIFY THE DISMANTLING DECREES OF TWO INBS ON THE SITE

The decrees governing the clean-up and dismantling operations at the CEA Fontenay-aux-Roses centre are currently effective up to 2 July 2017 for INB 165 and up to 2 July 2018 for INB 166. Within this scope, two files requesting new decrees have been sent to the relevant authorities - the ASN and the Nuclear Safety and Radiation Protection Board (MSNR) under the Ministry for Ecology, Sustainable Development and Energy - so they can be examined and submitted for public enquiry. The request mainly seeks to extend the deadlines required to decommission the facilities according to the new dates defined in the master schedule for projects managed at the centre, as well as to define a review of the final state by proposing an innovative consolidated dismantling plan. A contractual milestone was met by the CEA when the files were sent to the ASN within the deadlines. These files mark the end of discussions between the public authorities and the CEA, illustrating the CEA's proactive intention to continue its dismantling and waste removal operations which are already well underway.

Antinea shielded line at Fontenay-aux-Roses (left) and the dismantling of a fume cupboard (right).

PROGRESS IN DISMANTLING INB 165: THE ANTINEA SHIELDED LINE HAS BEEN COMPLETELY DISMANTLED

The Antinea shielded line in Building 18 of INB 165 was made up of five alpha containment boxes. It was designed to implement a process for manufacturing Pu-238 metallic fuel to be used as a heat source to provide energy to isotopic power generators for pacemakers. This shielded line was then reconverted so it could be used to prepare sealed sources based on actinide oxides or mixtures based on target elements such as beryllium. Owing to the high neutron emission from compounds found in the cells, they were shielded by means of boxes made from low-carbon steel filled with water. Following a study phase, the dismantling work started in July 2014 with the removal of the biological shielding and the dismantling of a fume cupboard. The first containment was removed in March 2015. The four remaining containments were transferred to a special room for interim storage to continue dismantling operations. They are now awaiting authorisation to commence cutting operations. The final stage of this dismantling process was finalised at the end of October 2015 with the frame treatment. This is the 11th shielded line to be dismantled at the Fontenay-aux-Roses centre from a total of 17 that existed in 1999. Two other shielded lines are being dismantled and four lines are still in operation, including the Petrus shielded line which will be the last to be dismantled in Building 18.

REMOVAL OF THE REMAINING HIGHLY RADIOACTIVE EFFLUENTS ON THE SITE

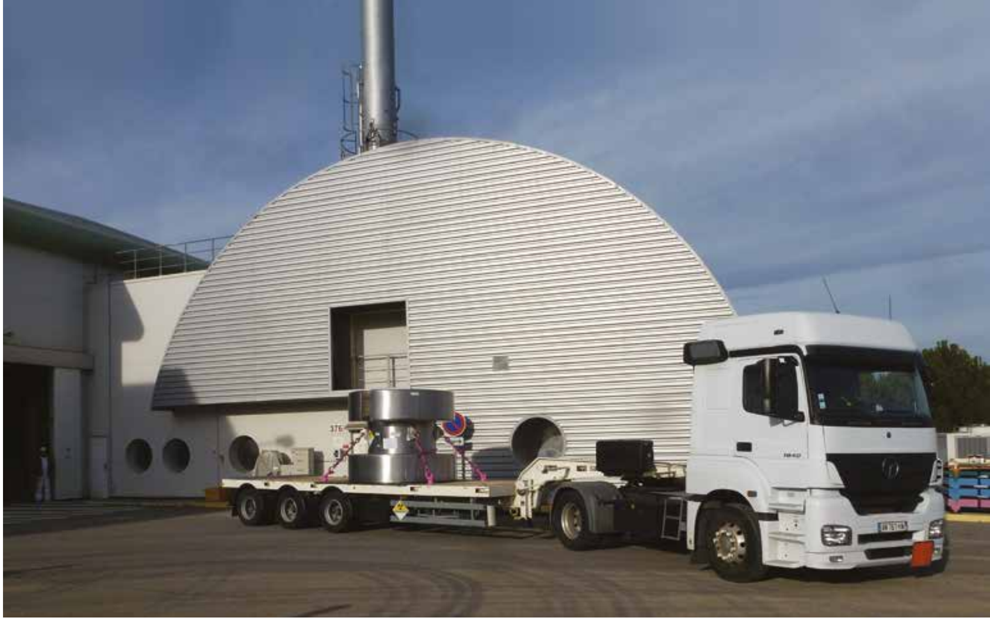
The last highly radioactive effluents were removed from the Fontenay-aux-Roses site in 2015. This concerned a total of 10 m^3 of alpha effluents produced in Building 18 of INB 165. Four transport operations were required to transfer this waste to the Marcoule liquid effluent treatment plant (STEL) using the LR 56 packaging. These aqueous effluents had been produced by the building clean-up operations, including the treatment of radioactive effluents from the Petrus shielded line.

SACLAY

TREATMENT OF TANKS FROM THE SACLAY HIGH-LEVEL LABORATORIES (LHA) COMPLETED

Among the equipment and rooms to clean up or dismantle in these hot laboratories (INB 49), there are 30 radioactive effluent tanks grouped into pairs that are located outside the buildings. Installed in the 1970s, each tank was placed in a buried metal liner that was connected to the adjacent cell via a system of pipes laid in trenches. The last of these 30 tanks was removed in April 2015, which was a key milestone in the dismantling of the facility itself. The operations were carried out in a manner similar to the 14 pairs of tanks: each tank was removed from its location and cut up in an airtight work area. The working conditions were adapted to the risk of contamination and the type of radioelements present. Two identical airtight work areas designed for nuclear environments were built to carry out these operations safely. The 28 metal liners were also cleaned and the stainless steel skins guaranteeing leaktightness with these liners were also removed. These operations took place in airtight work areas made from lighter structures. Concerning the last pair of tanks connected to the hot cell in which caesium sources were manufactured, the working conditions required setting up biological shielding above the tanks to protect the workers and neighbouring buildings from irradiation. The insides of the tanks were cleaned by sandblasting so each tank could be removed from its location and cut up in the airtight work area.

One of the tanks before dismantling (top) and while being cut up (bottom).



First stainless steel package from pit No. 6 (INB 56) arriving at the Cedra facility on the Cadarache site.

GRENOBLE

DECOMMISSIONING THE SILOÉ REACTOR

After having gone critical for the first time in 1963 and then shut down in 1997, the Siloé reactor was officially decommissioned by ministerial order dated 12 February 2015, thereby validating the corresponding ASN decision. Siloé is therefore the third and last reactor on the CEA Grenoble centre to be decommissioned following Siloëtte in 2007 and Mélusine in 2011. The area that has been freed up by the dismantling of these reactors will be used to build R&D facilities devoted to biomass studies.

CADARACHE

The clean-up and dismantling activities at Cadarache concern a number of different INB sites, as well as various operations to retrieve and condition waste and/or to reprocess and transfer spent fuels. Several key milestones were reached in 2015.

INTERIM STORAGE FACILITY FOR SOLID RADIOACTIVE WASTE (INB 56)

INB 56 is a facility designed for the interim storage of very-low-level, low-level and intermediate-level waste. Commissioned in the 1960s, it has been progressively replaced by the Cedra facility since 2006. Radwaste retrieval and conditioning operations are therefore carried out within this context. These operations concern two areas of the facility: 1) the interim storage depot comprising warehouses, three experimental fuel storage pools which have already been emptied, and six pits containing long-lived intermediate-level waste, and 2) the area comprising five trenches mainly filled with short-lived intermediate-level waste and a warehouse containing very-low-level waste. The year 2015 marked a key milestone, as it saw the retrieval of waste thanks to the implementation of equipment that had required months of investigation, design and technical & safety assessments before it could be used. Therefore, the first stainless steel package from pit No. 6 could be removed and transferred to Cedra in December 2015. The removal of the 191 stainless steel packages stored in this pit is a top-priority safety objective (OPS) for which the deadline will be defined according to the time it takes to retrieve about ten packages. Furthermore, one of the five cells in Pit No. 3 was completely emptied of its waste in October, making it possible to continue retrieving waste from a second cell. Lastly, the waste retrieval operations in trench No. 2 were continued at a pace of about 5 m^3 per month, this being another top-priority safety objective for late 2017.

SOLID WASTE TREATMENT PLANT (STD)

The treatment plant for radioactive effluents and solid waste (INB 37) at Cadarache can be divided into two sub-systems: one for treating liquid effluents (STE) and the other for treating and conditioning solid waste (STD). The first is currently shut down and has been replaced by the Agate facility. The lifetime of the second sub-system must be extended and is thus being refurbished. This involves dismantling old obsolete equipment in a nuclear environment while complying with a schedule and scenario that must be compatible with the refurbishment project. Among the achievements of 2015, it is worth mentioning the end of dismantling work on the shielded cell containing the 250-tonne press, which was a prerequisite to dismantling the press itself.

CROSS-DISCIPLINARY PROJECTS FOR CLEAN-UP AND DISMANTLING

To make progress in clean-up and dismantling projects along with the retrieval and conditioning of waste, cross-disciplinary projects are needed to coordinate all of the different activities involved. These activities range from transport to waste & material flow management and operation of nuclear service facilities, as well as R&D needed to support all of these worksites.

The new Tirade transport cask.

TRANSPORT

Transport is a field that covers all operations and conditions related to the carriage of radioactive materials, from the design of transport casks through to waste unloading and acceptance procedures. In this context, the DEN is responsible for defining and operating a fleet of casks designed to transport different types of radioactive materials found at the CEA. In this field, there are three main operational activities: 1) transport operations, 2) operational maintenance and regulatory compliance of the transport cask fleet, and 3) design, construction and series production of new transport casks and related equipment.

TIRADE: A NEW CASK DESIGNED TO TRANSPORT SOFT HOUSEKEEPING WASTE[1]

As part of its strategy to extend its fleet of transport casks, the DEN has designed a new cask called Tirade which will be used solely to transport radioactive waste. Its design incorporates all the operational requirements associated with nuclear facilities, e.g. weight, overall dimensions, loading & unloading methods, type of waste drums to transport, etc. It also meets the latest safety case requirements, specifically in terms of radiological and internal explosion risks inherent to radioactive material subject to radiolysis or thermolysis. Several innovative developments and specific materials have thus been employed to guarantee, for instance, the robustness of the cask closure system in the event of an explosion or drop. The cask also boasts highly efficient biological and thermal shielding, which is required to transport activated waste. The year 2015 was marked by the commissioning of this new transport cask, including the first transport operation with an empty cask from Fontenay-aux-Roses to Cadarache to test both the loading/unloading procedures and the transport configurations.

(1) Also called "technological waste".

ACTIVE COMMISSIONING AND FIRST UNDERWATER LOADING OF THE IR200 TRANSPORT CASK

A highlight of 2015 was the active commissioning and first immersion of the new CEA transport cask called IR200 in the pool of INB 72 at the Saclay centre. A first basket of 26 spent fuel rods followed by a second basket of 23 rods were loaded underwater. This was the first time that spent fuel had been loaded into a cask fully immersed in this facility. The loaded IR200 cask was dispatched to the LECA-STAR facility at Cadarache. The spent fuels will be reprocessed and reconditioned here before being placed in interim storage in the Cascad facility also located at Cadarache.

These two operations are part of the top-priority safety objective which aims at removing all spent fuels from INB 72 by late 2017. INB 72 was designed to manage the current flow of radioactive waste produced by the scientific and operational activities at the CEA Saclay centre. This facility is also used for the interim storage of legacy waste: soft housekeeping waste, unused radioactive sources, and irradiated fuels, which are stored in bunkers, in pits and in a pool.

The IR200 transport cask at the bottom of the pool in INB 72 at Saclay.

WASTE AND MATERIAL FLOW MANAGEMENT

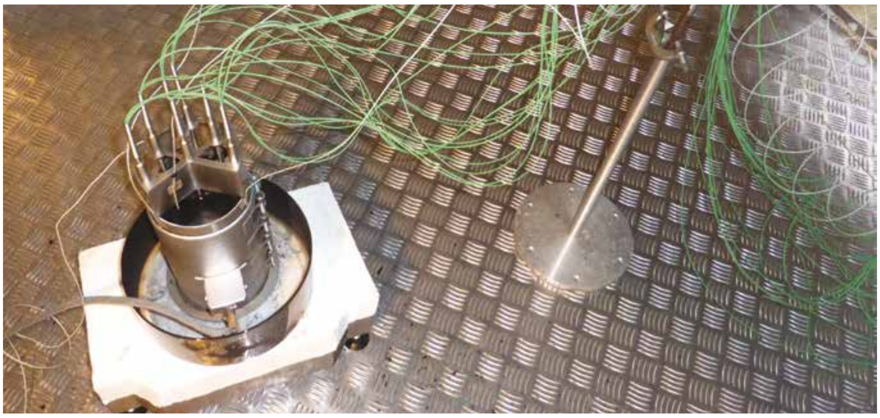
The objective behind the management of radioactive waste, materials and unused fuels is to optimise both the R&D activities and the clean-up and dismantling programmes at the CEA.

One of the CEA's main objectives is to provide operational treatment and (interim) storage systems for all waste categories, as well as the online capability for transferring waste to Andra's operational repositories (Cires and CSA) under optimised technical and economic conditions. Another key objective is to relie on disposal sites in the future that can deal with all high-level (HLW) and long-lived intermediate-level waste (LL-ILW) packages, as well as all long-lived low-level waste (LL-LLW) packages.

CIGÉO ACCEPTANCE SPECIFICATIONS FOR HLW AND LL-ILW PACKAGES FROM THE CEA

The CEA is carrying out technical and scientific studies with respect to the future acceptance of its HLW and LL-ILW packages into Cigéo, the deep geological waste repository of which Andra is the project owner. It is also helping with the implementation of operational acceptance specifications for its HLW and LL-ILW packages destined for disposal in the Cigéo facility. As owner of mostly LL-ILW packages, the CEA defines and carries out its own R&D programmes on bituminised sludge (about 15% of the design inventory for LL-ILW packages at Cigéo), cemented packages containing various soft housekeeping waste (about 10% of the LL-ILW inventory for Cigéo), and waste containing magnesium in metal form (spent cladding from natural uranium graphite gas reactors).

One of the key milestones of 2015 was when the results of the risk control assessment - particularly on fire risks - of bituminised waste packages in a deep geological repository were presented to the French national assessment board (CNE). This four-party research programme between the CEA, Andra, AREVA and EDF produced a file of 17 technical reports. The studies confirmed the fact that concrete disposal packages containing four drums of bituminised sludge remained mechanically sound when subjected to a fire in a conservative thermal environment, i.e. 2 hours at 1,000°C. Overheating due to the external heat flow of the bituminised drums in the concrete packages remains very limited and does not result in self-heating or self-ignition. These results, combined with experiments conducted on a representative scale and thermochemical modelling, corroborate the fact that fire risks are controlled when these packages are placed in a deep geological repository.



Experimental set-up for thermal stress tests on bituminised sludge coatings on a scale of 1 kg.

TRITIATED WASTE STUDIES

As part of commitments undertaken by France as host of the ITER project, the CEA is providing technical support - via Agence ITER France - to ITER Organization in the field of radioactive waste management and dismantling. In this context, an innovative approach to tritiated waste management has been put forward. Based on a scenario defined by a specific waste inventory and related source term, the most appropriate management technique involves a multi-criteria analysis that takes into account aspects such as safety, environmental protection, technical feasibility and costs. Interim storage appears to be the solution suitable for all the types of waste in question. Heat treatment - either by heating or incineration - has been identified as a relevant process for tritiated soft housekeeping waste since it results in a smaller waste volume with a higher detritiation factor. It does, however, require setting up a secondary waste management route and a detailed assessment of the financial gain. An article called *Tritiated waste management opportunities based on the reduction of tritium and out-gassing* and its poster, describing the methodology and results of the CEA's studies, were awarded a prize at the 2015 *Waste Management* international conference which is held every year in Phoenix, Arizona, in the US. This conference attracts around 2,000 scientists, engineers, managers and students from around the world. The study will be continued in 2016 and will contribute in the definition and the technical & economic optimisation of Intermed, the future interim storage facility for tritiated waste that requires a cooling period of about 50 years to reduce the tritium inventory by a factor of 16.

NUCLEAR SERVICE FACILITIES

The CEA relies on a broad range of nuclear service facilities to manage its radioactive waste and nuclear materials. These facilities are designed to treat, condition and temporarily store nuclear materials, spent fuels, liquid effluents and solid waste generated by R&D programmes on clean-up & dismantling. As some of these facilities date back to the construction of the centres, the CEA has agreed to undertake a major programme of reform (shutdowns, new build and refurbishment) to meet future needs and comply with new safety requirements.

LAYING THE FIRST CONCRETE BLOCKS OF THE DIADEM INTERIM STORAGE FACILITY

Pending the commissioning of Cigéo by Andra, the CEA has identified the need to build an interim storage facility for its highly activated and/or alpha-emitting waste produced by five CEA centres. Following the favourable outcome of the public enquiry free of any reservations which took place in June and July 2014, the construction of the Diadem facility was launched in 2015 on the Marcoule site where most of the waste in question is produced. The first concrete blocks were laid in May 2015. The facility is expected to be commissioned in late 2018 and should operate for about 50 years.

Director of the CEA Marcoule centre laying the first concrete blocks of the Diadem facility.

R&D FOR CLEAN-UP AND DISMANTLING

With its expertise in nuclear clean-up and dismantling, the DEN has organised its R&D programmes in this field into six different categories: 1) Assessing the radiological condition of its facilities and soils, 2) characterising waste, 3) performing safe, economically viable operations in hostile environments, 4) decontaminating structures and soils, 5) treating waste and effluents in optimal conditions, and 6) developing and using tools and methods for costing and managing materials, waste and transport operations. Focus on a few key actions.

SEVEN PROJECTS CHOSEN CONSECUTIVE TO ANDRA'S CALL FOR PROJECTS UNDER THE FUTURE INVESTMENTS PROGRAMME (PIA)

The DEN is involved in Andra's call for projects under the Future Investments Programme (PIA), which is devoted to optimising the management of radioactive waste resulting from dismantling activities. Out of the twelve proposals involving the DEN for the first round, seven were chosen by Andra in 2015. They concern the development of effective technologies and processes for dismantling operations at the CEA. The needs in this field are far and wide: fibre dosimetry measurements by optically stimulated luminescence (OSL), neutronic mapping, autoradiography for the non-destructive measurement of beta- and alpha-emitting radioelements, 'in-can melting' vitrification process to condition long-lived intermediate-level waste, new waste conditioning matrices that are less sensitive to radiation, and decontaminating melting of tritiated waste or steels containing uranium. A total of 19 new proposals were prepared late 2015 for selection in 2016.

FIRST ACTIVE COMMISSIONING OF THE MAESTRO ROBOTIC ARM COUPLED WITH HIGH-POWER LASER CUTTING

Among the innovative processes developed by the CEA for its dismantling sites, the remotely operated robotic arm called Maestro - built in collaboration with its industry partners - stands out as a pure technical exploit. It provides access to highly irradiating areas impossible to reach by operators, and is used to insert various characterisation, decontamination, cutting and gripping tools that are needed to accomplish the different tasks involved in a dismantling site. In 2015, the Maestro arm was used several times in active conditions, with the start of dismantling operations on a shielded cell at the Marcoule pilot unit (APM) in June, followed by the dismantling of dissolvers in the UP1 plant at Marcoule at the end of the year. The dismantling of the dissolvers marked a world first and was the fruit of many years of studies and development at the CEA: made of metal that is extremely difficult to cut mechanically considering its hardness and thickness, these dissolvers were remotely cut by Maestro using a laser technique.

Remotely operated Maestro arm inside a shielded cell of the Marcoule pilot unit (APM).

PROMOTING RESOURCES AND EXPERTISE

The DEN's R&D work is mainly performed in the context of agreements with large industrial companies such as EDF and AREVA, but it is also illustrated by its considerable ability to carry out technology transfers. The DEN promotes the resources and expertise it has developed for the nuclear industry on an international scale and also to non-nuclear industries.

Elemental and isotopic analysis of uranium and plutonium samples in glove boxes at Saclay.

LOW-UNCERTAINTY ISOTOPIC ANALYSIS

In 2015, the International Atomic Energy Agency (IAEA) launched an international inter-laboratory comparisons programme, known as RORO, for measuring uranium (U) and plutonium (Pu) isotopic composition by mass spectrometry as part of global efforts to prevent nuclear proliferation. Researchers from the Nuclear Isotope and Elemental Analytical development Laboratory (LANIE), which has been a member of the IAEA's NWAL[1] for nuclear material analysis since 2014, took part in the programme. Their mass spectrometry analysis of five U and Pu samples - with a « thermal ionisation source » or « multi-collection plasma source » depending on the case - obtained results with low uncertainties on minor U isotopes (234 and 236) in the order of a few per thousand.

DEMONSTRATING SUPERCRITICAL CO_2 EXTRACTION OF NEUTRAL LIPIDS FROM MICROALGAE

The DEN's research teams at Marcoule have been working, in collaboration with industrial and academic partners, on a project to promote the large-scale cultivation of a native microalga[2] in open saline environments still unused so as to create a bio-refinery to produce bioenergy (biomethane and biodiesel) and bioproducts. This study has highlighted the considerable potential of microalgae as a source of high added-value lipid derivatives like beta carotene and omega 3, as well as the prospects for supercritical CO_2 extraction of neutral lipids from 20 kilos or so of dried algae. It has helped demonstrate the maturity of this technology compared with other processes, such as microwave or agro-solvent techniques. The technological expertise gained by the DEN in the field of supercritical CO_2 is now subject to patent assignments. The start-up company DFD progressed into its growth stage in 2015 following its first sale of CO_2 cleaning machinery for industrial mechanical components.

Microalga before extraction (left); microalga after extraction: CO_2 extract of beta carotene (right).

DEN SCIENTIFIC AND TECHNICAL EXPERTISE SUPPORTS THE ITER PROJECT

ITER is an experimental tokamak-type fusion prototype currently under construction in Saint-Paul-lez-Durance, south of France. The CEA has been involved in this international research project since the design phase, with F4E[3] (EU domestic agency) focusing on activities where DEN teams possess the necessary technical and scientific expertise (materials, mechanics and neutronics, for example). ITER Organization is responsible for the research facility's design, construction and operation as well as its final shutdown. As such, it has launched calls for tenders for various operation and maintenance projects to which the CEA has responded on the basis of the DEN's experience in these fields. A new 3-year contract was signed in November 2015 through which the DEN will bring its safety and maintenance expertise for the tokamak equipment and the hot cells. New invitations to tender are expected and a second contract relating to the expertise required for transfers between the tokamak and the hot cells is now also at the final signature stage.

(1) NetWork of Analytical Laboratories.

(2) Dunaliella salina is a genus of microalga which grows naturally, especially in hypersaline environments.

(3) Fusion for Energy - European Union (EU) organisation managing Europe's contribution to ITER.

Laser cutting of the corium simulant.

Gamma camera based on a scintillator coupled with a compact gamma spectrometry probe.

FRENCH DISMANTLING TECHNOLOGIES FOR FUKUSHIMA

A French proposal backed by Onet Technologies and based on technologies developed by the CEA has been awarded a subsidy from the Japanese Ministry for the Economy, Trade and Industry (METI) following a first international invitation to tender. The project involves the study and testing of cutting operations on molten fuel debris (corium) from the Fukushima Daiichi reactors carried out under inactive conditions in air and under water.

The CEA has brought its corium expertise into play in this study, as well as the remote-controlled laser cutting system developed as part of its own dismantling projects. This system, which is easy to operate remotely, was designed with a high positioning tolerance for cutting heterogeneous layers of materials, and produces fewer aerosols than the majority of other thermal techniques available.

This initial study, submitted in March 2015, was well received by the Japanese. Following a new international call for tenders, this technology was reselected mid-way through 2015 for further in-depth studies and testing on more realistic simulants to be conducted in 2016 and 2017.

This study also echoes the success of the remote-controlled laser cutting operations completed using the Maestro system at the end of 2015 to dismantle the dissolver tanks in the UP1 spent fuel reprocessing plant at the CEA's Marcoule site.

PARTNERSHIP WITH ENGIE ON RADIOLOGICAL CHARACTERISATION

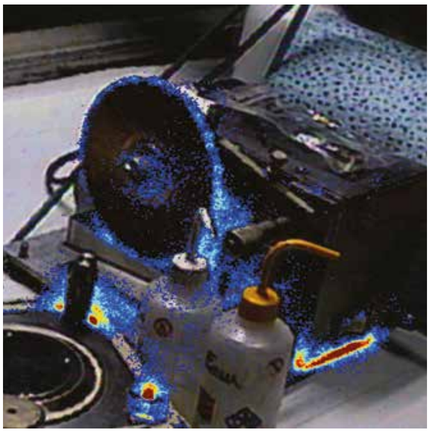
Laborelec, the ENGIE group's research and competence centre for electrical power technologies, is responsible for preparing the clean-up and dismantling programme for the Belgian Doel and Tihange nuclear power plants, in particular the two reactors at the Doel plant, originally scheduled for final shutdown in 2015 before their service life was extended by 10 years. The DEN and Laborelec collaborated in 2015 in the field of radiological characterisation to determine the initial radiological state of facilities before dismantling, an issue which presents a significant challenge to developing dismantling scenarios. The collaboration also involved the development of a gamma camera (based on a scintillator and coupled with a compact gamma spectrometry probe) and its associated instrumentation, on the basis of a DEN patent. This partnership is still ongoing in 2016, with work continuing on developing algorithms to refine the location of gamma sources in space directly using data from the images taken.

ALPHA CONTAMINATION MEASUREMENT CAMPAIGN CONTRACT FOR SELLAFIELD

Sellafield Ltd has introduced an initiative to identify innovative technologies that can help control the costs of dismantling its thermal oxide reprocessing plant (THORP). The alpha contamination characterisation and measuring system developed by the CEA was selected within the scope of this initiative in 2015 for an experimental campaign to be conducted on-site mid-2016. This system has already been tested under active conditions, most notably in the plutonium technology workshop (ATPu) at Cadarache. These tests at Sellafield will help raise the system's profile with a view to developing it on an industrial scale for the benefit of the CEA's dismantling worksites.

This initial exchange with Sellafield Ltd has provided an opportunity for the two parties to establish contact with a view to working together on common projects in the future.

Their joint response to the Euratom H2020 call for the thermal treatment of waste resulting from dismantling operations is just one example of such cooperation.



Locating alpha contamination in a glove box in the Atalante facility at Marcoule.

CENTRES

The Nuclear Energy Division (DEN) carries out research activities at three centres: Saclay, which focuses on front-end research, simulation, materials and chemistry; Cadarache, which specialises in reactors and fuels; and Marcoule, which concentrates on the front-end and back-end of the fuel cycle.

Atalante facility where studies are being conducted on americium separation processes.

MARCOULE: R&D FOR THE FUEL CYCLE AND CLEAN-UP AND DISMANTLING PROJECTS

With 60 years' experience of pioneering innovation in the French nuclear industry, the Marcoule site is home to the DEN's research teams and facilities involved in the nuclear fuel cycle. This centre also ensures the operational supervision of large-scale clean-up and dismantling projects at both Marcoule and other civilian nuclear sites belonging to the CEA.

R&D FOR THE FUEL CYCLE

On an industrial level, the Marcoule centre has continued its studies undertaken on behalf of AREVA into optimising operation of the fuel cycle plants, both for the industrial front-end units (mainly the Comurhex conversion plant at Malvési) and for La Hague spent fuel reprocessing and recycling plant.

- **New dissolution process** - A new dissolution and digestion process was developed for special nuclear fuels in 2015, featuring enhancements to both future process modelling and experimentation techniques, including, for example, dissolution of a batch of fuel pellets from fast reactors.
- **R&D MOX[1]** - Progress has continued on the transfer of MOX fuel R&D activities from Cadarache to Marcoule, with the arrival of the first equipment deliveries and the fitting out of new research laboratories for non-active conditions. The targeted revival of this activity by 2017 will enable the CEA teams involved to work more closely with their end customer - the AREVA MELOX plant at Marcoule. This new area of R&D for the centre will also provide the opportunity to consolidate the breadth of expertise and R&D resources available at the Atalante hot laboratory.
- **Separation of americium** - Teams at Marcoule have continued an experiment aimed at demonstrating the feasibility of recycling americium extracted from spent fuel on a laboratory scale within the scope of studies financed by the public authorities under the terms of the 2006 legislation on sustainable management of radioactive materials and waste. An « integral » extraction test was conducted using the EXAm process developed by the CEA, resulting in the recovery of several grams of purified americium from spent fuel from the EDF fleet. Recovery of this radioelement can now lead on to the development of minor actinide-bearing fuel pellets and their subsequent irradiation in a fast reactor with a view to demonstrating their transmutation capability.
- **Vitrification of radioactive waste** - In addition to the support provided to the cold crucible in-plant vitrification campaigns for uranium-molybdenum fuels, the CEA-AREVA joint vitrification laboratory's team of experts at Marcoule has conducted several incineration-vitrification tests of the Pivic process designed for treating mixed "technological" waste (metal and organic waste) for the MELOX and La Hague plants. The centre is also continuing its R&D activities on the long-term behaviour of waste packages destined for Andra's Cigéo deep geological repository, most notably by launching a study, under active conditions, into the alteration of industrial glass under geological disposal conditions.

Induction-heated crucible in which waste is incorporated into the molten glass.

(1) Mixed oxide fuel (a mixture of uranium and plutonium oxides).

Control room operator (right) controlling the Maestro robot arm in a Marcoule pilot unit (APM) cell (left).

CLEAN-UP AND DISMANTLING PROJECTS

Significant advances have been made on the clean-up and dismantling worksites underway at Marcoule. The main challenge is still to reduce the "mobilisable" source term in the facilities, as reiterated by the safety authorities (ASN and ASND) at the time of their joint visit to the centre in September.

- **Arrival of the Maestro robot arm** - 2015 was a landmark year which saw the commissioning of the first two Maestro robot arms under active conditions at the Marcoule facilities after more than 10 years'collaboration between the CEA and Cybernetix as part of a joint development programme. This robust, versatile remote controlled system will enhance the reliability of hot cell sites. It has already made it possible to begin the complex task of cutting dissolver tanks in the "MAR 200" area of the UP1 spent fuel reprocessing plant whilst dismantling operations using mechanical cutting techniques could be initiated on a hot cell at the Marcoule pilot unit (APM). The Maestro robot arm is associated with a laser cutting process developed by the CEA.
- **Waste removal** - The removal of legacy waste still poses a major challenge for the centre. Operations have been carried out on the various facilities concerned in and around the UP1 plant. 2015 was marked, in particular, by the installation of a cementation process in the old fuel decladding facility, which has made it possible to start pumping and cementing sludge present in the bottom of the pits.
- **First concrete laid for Diadem** - The first concrete for the future Diadem interim storage facility was poured in the spring of 2015. This facility is intended for temporary storage of activated waste from the CEA's clean-up and dismantling worksites, before they are transferred to Andra's disposal facilities.
- **Caesium decontamination process** - Research conducted at Marcoule within the scope of R&D set up to optimise the clean-up and dismantling processes has resulted in the development of a pilot unit for flotation foam decontamination to treat caesium contaminated soil. This process offers the potential for application in Japan for the remediation of contaminated land in the region of Fukushima.

FOCUS ON

CONSTRUCTION OF THE NOAH FACILITY

The CEA Marcoule centre has undertaken to build a dedicated facility - NOAH - within the scope of the Phénix dismantling project, for treating the liquid sodium contained in the primary and secondary systems of this fast reactor which was finally shut down in 2009. This new facility will be used to transform the liquid sodium (mainly 1,500 tonnes from Phénix as well as a few low-volume batches of sodium from other CEA centres) into hydrated sodium hydroxide, before it is neutralised. Construction of the facility has progressed well; the concrete for the basemat was poured last summer and the first sections of shell wall were erected in the autumn.

60 ans MARCOULE

MARCOULE - 60 YEARS OF PIONEERING SPIRIT

The year 2015 marked the 60-year anniversary of the Marcoule research centre, an event which was celebrated in October. In addition to a ceremony for all staff attended by the CEA's General Directorate, the centre's facilities opened their doors to the families of all employees for a weekend. Almost 4,000 people took advantage of the opportunity to visit the 20 or so points of interest, taking in sights ranging from legacy reactors to the most cutting edge laboratories. A commemorative book comprising 60 employee portraits was also published, highlighting the centre's activities through some of the faces of those who are pushing the boundaries of research and development.

Concreted dome of the JHR reactor building.

Aerial view of the Cadarache site.

CADARACHE: RESEARCH ON REACTORS AND FUELS

Cadarache is the major European research centre devoted to low-carbon energy: nuclear fission and fusion, solar energy, and biofuels. The site is home to a wealth of expertise and skills, a wide variety of dedicated research tools - with three nuclear research reactors and technological platforms that are unequalled anywhere in the world.

REACTORS

- **Construction of the Jules Horowitz experimental reactor (MTR)[1]**
The Jules Horowitz Reactor (JHR) is currently being built on the Cadarache centre. The year 2015 was marked by the successful pouring of 730 m^3 of self-compacting concrete in a single operation that lasted 20 hours to consolidate the reactor building dome. About 85% of the civil engineering work has been completed and the manufacturing of mechanical equipment is well underway. Most of the reactor construction and equipment work packages have either been delivered or are underway. Having performed more than 20 inspections on the construction site since 2009, the French nuclear safety authority (ASN) has regularly highlighted its good condition.

- **Divergence of the Cabri research reactor in pressurised water loop configuration**
Undergoing refurbishment since 2003, the Cabri research reactor went critical for the first time in its new pressurised water loop configuration which is representative of the current fleet of pressurised water reactors (PWRs). The commissioning tests will continue up to 2017, the year the first test is expected to take place. The Cabri reactor will be used to conduct studies on the behaviour of fuels in accident conditions. The facility was refurbished for the IRSN as part of the Cabri International Programme (CIP).

SIMULATION

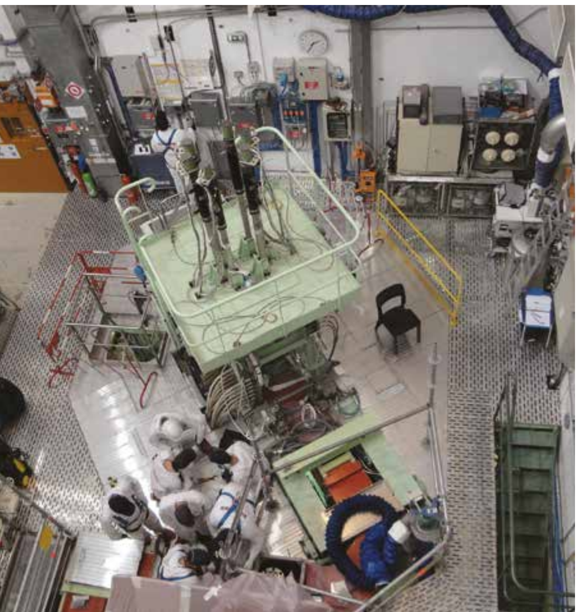
Numerical simulation is essential for developing reactors and their fuels. It is in this context that computational codes and schemes are developed by the teams at Cadarache. Focus on some key results of 2015.

- **Delivery of the NARVAL 2 code package for AREVA TA**
NARVAL is a neutronics code package used to design nuclear propulsion cores. At the time of its delivery, the CEA military applications division, the naval propulsion nuclear reactors joint technical service, and AREVA TA all gave their seal of approval for the choice of methods and potential of this code.

- **Delivery of the OSCAR code for EDF**
The new V1.3 version of the OSCAR 1 code designed to study the contamination of PWR systems was delivered to its industry partners, EDF and AREVA. Contamination control is a key industrial issue when it comes to reducing dose levels during unit outages while increasing reactor availability.

- **Development of the GERMINAL application for fast reactors**
The multi-year development plan for the second version of the GERMINAL application designed to simulate the behaviour of fuels and absorbers in sodium-cooled fast reactors (SFRs) has been defined up to 2024. The application of the PLEIADES software platform is actively contributing to the Astrid design studies, with GERMINAL being one of the codes used for the fast reactor type.

(1) MTR: Materials Testing Reactor.



Cabri test hall: view of the control rod operating platform (green part).

Test platform supporting Astrid R&D.

FUTURE NUCLEAR SYSTEMS

The Cadarache centre plays a key role in studies focusing on future nuclear systems, and more specifically in the development of the SFR integrated technology demonstrator called Astrid. Most of the test means needed to qualify the design options for this reactor are available on site at Cadarache. Tests were performed in 2015 on test platforms using either water or sodium as the simulating fluid. It is worth highlighting the first campaign of tests which involved injecting sodium into water in an open medium using a new sodium-water interaction device. These tests were performed to support the Astrid safety studies. The complex phenomena involved can be characterised by using a specific set of very refined instrumentation including an ultra-fast visualisation technique.

SUPPORT FOR INDUSTRIAL PARTNERS

The Cadarache centre plays an important role in R&D needed to support the current industrial-scale fleet, particularly in the fields of fuels and nuclear safety.

- **Fuel behaviour**
  A technical breakthrough in understanding fuel behaviour was made with the development of an innovative experimental device that directly measures pressure variations in a PWR fuel assembly mock-up. The data collected from this experiment is providing valuable insight into better understanding flow-induced vibrations, which is a key issue for PWRs.

- **Impact of accident conditions on fuel behaviour**
  The first test designed to analyse the thermal and mechanical behaviour of irradiated nuclear fuel during an accident transient was performed in the Mexiico facility in the DEN's hot laboratory called LECA at Cadarache. This test was carried out under the Nuclear Fuel Industry Research (NFIR) international programme run by the Electric Power Research Institute (EPRI) for a group of industrial companies and laboratories.

NUCLEAR CLEAN-UP AND DISMANTLING

As requested by Andra, the Cadarache centre uses its skills and experimental means to characterise waste packages so as to check that they comply with the specifications of the waste repositories. Within this scope, a new shielded cell called CADECOL has been operational since 2015. With its analysis and reconditioning capacities, this new facility of INB 156 can now comply with Andra's specifications for extremely stringent inspections of short-lived low- and intermediate-level waste (SL-LILW) packages.

Furthermore, the drain system installed under the laboratory for the study and experimental fabrication of advanced fuels (LEFCA) at Cadarache, which is designed to prevent soil liquefaction in the event of an earthquake, is now operational. This complies with the ASN decision for which the corresponding file was made available to the public in November 2015. In 2003, this facility underwent a safety review which concluded that it could continue operating on the condition that a refurbishment programme was deployed taking into account the risk of soil liquefaction.

KNOWLEDGE HUB

In 2015, numerous events covering a broad range of subjects were organised: severe accidents, irradiation of materials, nuclear data, instrumentation, nuclear medicine and cyber-security.

The new agreement with the University of Aix-Marseille was signed. This agreement will allow for the creation of numerous structures, partnerships, research programmes, training courses and joint scientific events covering a variety of subjects. Synergies with the French National Centre for Scientific Research (CNRS), engineering schools and other research organisations strengthen the CEA's reputation as a knowledge hub.

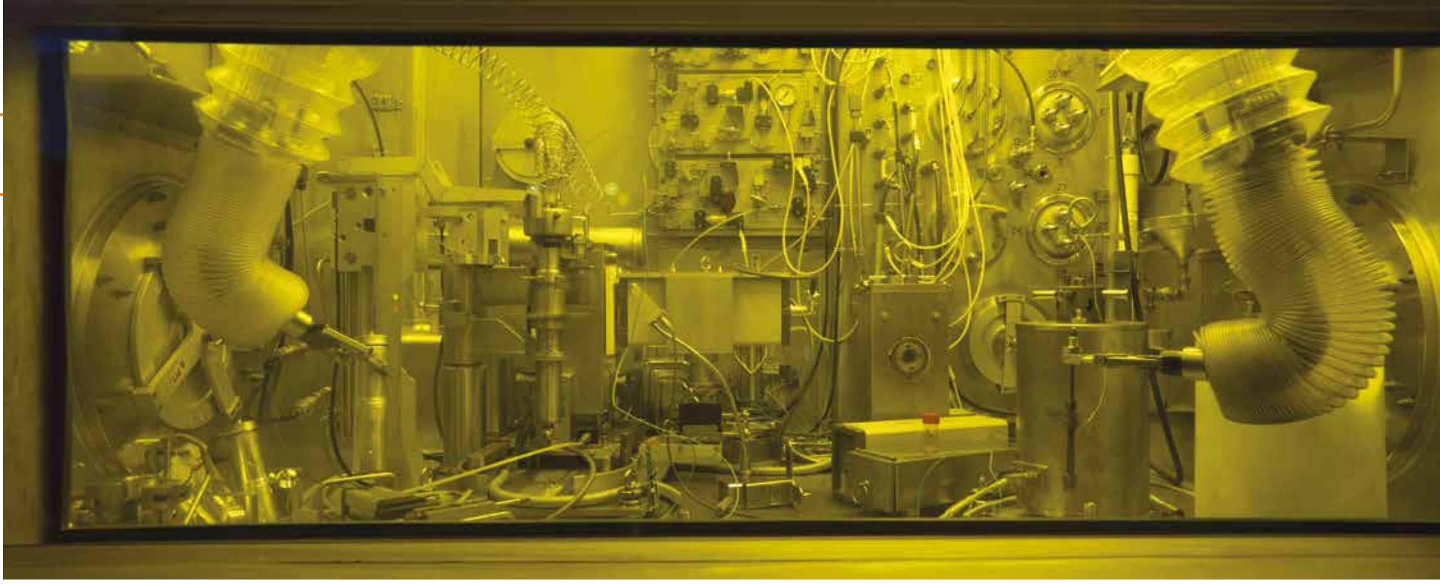
Cadarache celebrated the 20th anniversary of its scheme called Cadarache Jeunes which organises visits, especially for high-school students in the region. To fête the occasion, the Cadarache centre decided to invite the teachers and supervisors this time.

To appeal to a broader general public, it also set up a new system to welcome individual visitors, thereby adding to the total of more than 10,000 group and school visitors per year. Cadarache also organised a science fair in the town of Sainte-Tulle which attracted a large younger audience. In addition to these events, an Open Day was organised during which 2,500 family members and friends were able to visit the centre.

Staff from the Cadarache centre have also attended more than 40 meetings held by the relevant local information commissions.

SEVERE ACCIDENT STUDIES

A world-first was achieved when the formation of a debris bed during corium-water interaction was monitored by X-ray imaging as part of studies on severe accident carried out at Cadarache. The fifth test of the Verdon programme was also performed at Cadarache within the scope of the International Source Term Programme (ISTP), involving EDF, ENGIE, US-NRC, JAEA and the IRSN. The goal is to study the behaviour of fission products generated in PWR fuel which can potentially be released during an accident up to core meltdown.



Léci is where the examinations into the reference cladding material considered for the Astrid demonstrator were conducted.

SACLAY: NUCLEAR SCIENCES AND SIMULATION FOR REACTORS AND THE FUEL CYCLE

The scientific activities carried out at the Nuclear Activities Division at Saclay cover three main disciplines: simulation, materials and chemistry.

SIMULATION FOR REACTORS

Version 1.2 of Apollo3®, the new multi-purpose neutronics code developed by the DEN, was distributed to the industrial partners, AREVA and EDF, at the end of December 2015. The aim of Apollo3® is to replicate the phenomena occurring in the fuel assemblies in both thermal neutron reactors (PWRs) and fast reactors as closely as possible. It allows innovative computational schemes to be developed across all « cell, assembly, core » scale levels, offering a significant improvement in the compromise between precision and computing time. The primary deliverable is a one-step core computation model, as compared with the existing two-step method. An initial phase was completed in 2015 with computation of the Astrid SFR demonstrator core and of a 3D PWR core with advanced modelling of the reflector.

R&D FOR 2ND AND 3RD GENERATION REACTORS

The beginning of 2015 marked the start of the first experiments conducted on the MARS beamline at the Soleil synchrotron facility. These experiments were performed on samples of highly irradiated materials taken from PWR cores, such as zirconium-based fuel cladding and stainless steels from vessel internals structures. This research has helped improve understanding of the effects of irradiation on the microstructure of the analysed materials.

R&D FOR 4TH GENERATION REACTORS

Sections of 15-15 Ti steel cladding (the reference cladding material considered for the Astrid demonstrator) which had been irradiated in the Phénix reactor at Marcoule were delivered to the Léci[1] in April 2015 to characterise their post-irradiation behaviour. The examinations performed involved density measurements, mechanical tests (traction and creep) and microstructural observations. The results have served most notably as the basis for the synthesis report for the Astrid preliminary design studies on matters relating to cladding materials.

FOCUS ON

FINAL SHUTDOWN OF THE OSIRIS REACTOR

The Osiris research reactor was finally shut down on 16 December 2015. This facility had been conducting research into materials and fuels for current and future nuclear power plants for almost 50 years, and had also produced radioelements intended for medical and industrial applications. Its mission was accomplished successfully by teams working at the reactor right up until this final stage.

Osiris teams gathered inside the reactor hall.

(1) Léci is a hot laboratory located at Saclay, dedicated primarily to characterising irradiated materials.

(2) Oxygen-deficient environment.

(3) French national supercomputing tools.

(4) Partnership for Advanced Computing in Europe.

R&D FOR THE BACK-END OF THE FUEL CYCLE

Materials such as stainless steels, zirconium and titanium used in the La Hague plant equipment require constant vigilance in terms of their resistance in a hot, concentrated nitric acid environment. Techniques to monitor the ageing of these materials and predict the service life of this equipment - both of which are incredibly complex procedures, especially in highly irradiated areas - would be considerably enhanced by a better understanding of the degradation mechanisms and how to model them. Significant progress was made in this area in 2015 on zirconium alloys. A link was established between surface properties and surface reactivity by combining the analysis of electrochemical impedance spectroscopy measurements with X-ray photoelectron spectroscopy surface analyses. The aim now is to extend this approach to other materials used in the plant. This understanding of corrosion mechanisms will enable better predictions to be made regarding the service life of equipment, and will eventually make it possible to suggest ways of optimising the materials used.

R&D FOR FINAL DISPOSAL

DEN teams at Saclay have conducted an experiment designed to quantify the corrosion rate of low-alloy steels on contact with the argillite host formation of the future Cigéo deep geological repository, and to identify the corrosion products released by this reaction. The experiment was completed successfully; after six years of corrosion at 90°C in anoxic[2] conditions, the last samples have now been recovered and the corrosion interfaces characterised at micrometre scale. The findings confirm a low corrosion rate of steels in compressed contact with argillite in temperature conditions consistent with those used for high-level nuclear waste disposal.

EXPERIMENTAL FACILITIES

- The new analytical nuclear R&D thermal-hydraulics testing facility at Saclay opened its doors on 17 December 2015. The intention is for this to become a dedicated research facility housing all analytical thermal-hydraulics and fluid mechanics equipment by 2017 for the purposes of simulating the behaviour of nuclear systems in normal, incident and accident conditions.
- On 14 September 2015, the International Atomic Energy Agency (IAEA) awarded its first ever ICERR label (International CEntre based on Research Reactors) to the Saclay and Cadarache centres. The DEN's experimental facilities - the JHR, Eole, Minerve, Isis and Orphée research reactors and the Léci and Leca-Star hot laboratories - will be recommended to institutions of the IAEA member States for the purposes of education, field training and joint R&D project development throughout the period 2015-2020.

Thermal-hydraulic testing equipment: on the top, a dedicated loop for validating the Cathare computer code, and below, a loop for creating a gas entrainment vortex for studying future fast reactors.

SCIENTIFIC INFLUENCE

Although titanium and zirconium have many similarities, researchers from the DEN, CNRS and Claude Bernard Lyon 1 University have shown that plastic deformation of these two metals evolves differently. It is commonly accepted that both metals should exhibit similar responses to mechanical stress. However, by combining microscopic experimentation and modelling techniques with the Genci[3] and Prace[4] computing resources, researchers have discovered two different dislocation motions in these materials. The aim now is to research the properties of various innovative alloys by means of predictive evaluation. These results were published in the August 2015 edition of *Nature Materials*.

CLEAN-UP AND DISMANTLING AT FONTENAY-AUX-ROSES

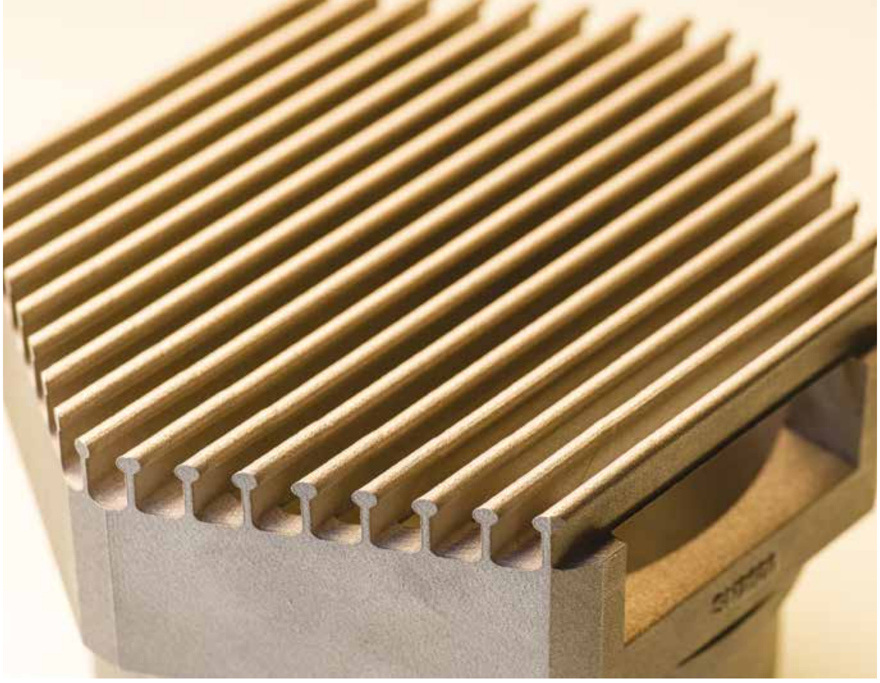
The first of the five alpha containment boxes from the Antinea shielded line was removed in March 2015. The four remaining containments were transferred to a special room for interim storage to continue dismantling operations. These are now awaiting authorisation to commence cutting operations. The final stage of this dismantling process was completed at the end of October 2015 with the frame treatment.

Operations to treat and subsequently remove waste resulting from the clean-up and dismantling worksites, as well as legacy waste stored in various buildings, have continued at a steady pace, as part of continued efforts to reduce the source term present in the site's two regulated nuclear facilities. Over the period 2013-2015, a total of eight hundred and fifty 200-litre drums of intermediate and low-level waste were removed from Building 91 and transferred to Andra's Aube disposal facility.

Interim storage of waste drums in Building 91 at the CEA's Fontenay-aux-Roses site.

PROGRAMME SUPPORT AND EXTERNAL RELATIONS

The DEN has set up an organisation to support its programmes, which includes the Cross-disciplinary Programme on Advanced Materials, the Scientific Division, the International Relations Unit, the Quality and Environment Division and the Institute for Techno-Economics of Energy Systems. All these units contribute to the success and visibility of the DEN's work.



Demonstrating the feasibility of producing a geometrically complex part intended for the nuclear industry using additive manufacturing.

CROSS-DISCIPLINARY PROGRAMME ON ADVANCED MATERIALS

Throughout 2015, the cross-disciplinary programme on advanced materials implemented various actions to enhance the CEA's visibility and external representation, and to promote strategic discussions and coordination.

DEVELOPMENT PLANS

Since 2015, this cross-disciplinary programme has organised its activities based around three main priorities.

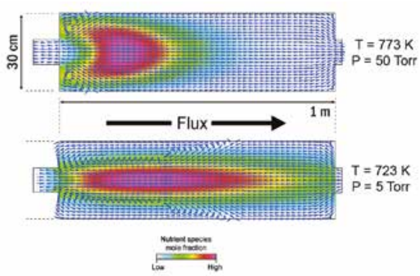
- **Materials development and process engineering.** Materials engineering represents the principal pillar of the programme, determining as it does the structure and properties of materials. It encompasses the development of robust processes, a review of "traditional" processes, the appraisal of emerging processes and the invention of innovative new processes in the field of nanomaterials and strategic metals recycling.
- **The development of new, made-to-measure materials:** multifunctional architectured materials; self-healing materials; bio-inspired materials; direct integration of functions into materials (sensors, etc.); digital design processes; high-throughput screening techniques... These are just some of the challenges thrown up by the growing complexity of technical specifications.
- **The science of ageing, sustainability and the lifetime of materials and resources.** With materials and components operating in possibly hostile environments, the overall sustainability of materials needs to be addressed through studies on behaviour prediction, characterisation during operation and characterisation on the simulation scales.

FIRST ONLINE TRAINING COURSE IN FRANCE ON ADDITIVE MANUFACTURING

Additive manufacturing represents the crossover between digital technologies and material science. This energy-efficient technology helps achieve a significant reduction in materials used. Furthermore, it can be used to manufacture individual parts with complex geometries in one piece using a whole range of materials (plastics, metals, alloys, ceramics), something which is currently extremely difficult to achieve using traditional methods such as moulding or machining. In 2015, in partnership with 3D4Pro, Supmeca and Alstom, the CEA helped set up the first MOOC[1] in French on additive manufacturing. This gives free, unrestricted online access to information about the technologies, industrial applications and challenges of additive manufacturing.

INNOVATION IN THE FIELD OF CHEMICAL VAPOUR DEPOSITION

The CEA, in partnership with CIRIMAT[2] in Toulouse and the CEMAM[3] laboratory of excellence in Grenoble, has filed a patent on the DLI-MOCVD process (direct liquid injection metal organic chemical vapour deposition) in a closed cycle with recycling of the metal-organic precursor[4]. This patent concerns the possibility of recycling the precursor in a continuous wave after it has been used in the deposition reactor. The process had been modelled as part of a thesis, making it possible to design a large-scale reactor. In order to continue developing this highly promising process, the CEA has set up a second project with CIRIMAT and an innovative small- and medium-sized enterprise called DEPHIS, the aim of which is to build a pilot reactor to demonstrate the benefit of this process for nuclear applications, and to assess its potential for use in other industrial sectors such as aeronautics and mechanics.



Benefit of using numerical simulation to optimise deposit homogeneity in a DLI-MOCVD pilot reactor.

(1) Massive Open Online Course.

(2) Centre inter-universitaire de recherche et d'ingénierie des matériaux (Inter-university Material Research and Engineering Centre).

(3) Centre of Excellence of Multifunctional Architectured Materials.

(4) Organic molecules containing metal atoms, which produce carbides, nitrides or carbonitrides by thermolysis.

R&D on compact sodium-gas heat exchangers for energy conversion.

The DEN Scientific Committee.

DEN SCIENTIFIC ACTIVITIES

The scientific division is responsible for the DEN's overall scientific strategy. Its primary tasks cover six main areas: relations with the High Commissioner for Atomic Energy, promotion of the DEN's scientific and technical expertise, organisation of the assessment of all of its units, identification of the major scientific challenges to be addressed, promotion of the DEN's scientific output and liaison with universities.

SCIENTIFIC ASSESSMENT

THE CEA SCIENTIFIC COMMITTEE

On 30 November and 1 December 2015 the CEA Scientific Committee examined the establishment's research into high-performance computing, simulation and data analysis. The DEN contributed to this exercise by way of three presentations (simulation strategy, software architecture, spotlight on neutronics) and four posters.

THE DEN SCIENTIFIC COMMITTEE

From 19 to 21 October 2015, the DEN Scientific Committee carried out an assessment of the research activities focusing on the optional gas turbine conversion system for sodium-cooled fast reactors (SFRs). This assessment led to the committee:

- Recommending a more in-depth approach to the technical and economic implications of this option;
- Pinpointing the risks associated with the sodium-gas heat exchanger in terms of fabrication, reliability, development planning right through to qualification;
- Maintaining an adequate range of studies on the water-steam conversion system, in order to make it a real fallback option.

FOCUS ON

CREATION OF AN ONLINE NUCLEAR SCIENTIFIC REVIEW

In 2015, the DEN created the online scientific review EPJ N - *Nuclear Sciences and Technologies* (affiliated to the *European Physical Journal*) with the support of the French Nuclear Energy Society (SFEN) and the publisher EDP Sciences. This review has already been referenced in the *Web of Science*.

SCIENTIFIC ACTIVITIES

SCIENTIFIC PUBLICATIONS

In 2015, the DEN's researchers produced 517 scientific papers in peer-reviewed journals, 120 of which were co-written with other international research laboratories.

BASIC NUCLEAR TRAINING

This training scheme provides all new recruits with cross-disciplinary scientific and technical knowledge and introduces researchers and engineers to the general basic nuclear culture around the research topics being studied within the DEN. In 2015, 28 participants who had already completed level 1 attended level 2 of this training scheme in Saclay.

PHD STUDENTS, POST-DOCTORAL STUDENTS AND RESEARCHERS AUTHORISED TO SUPERVISE UNIVERSITY RESEARCH (HDR)

In 2015, a particularly active search for cofinancing led to an appreciable increase in the number of new PhD students joining (92) - up +11% on 2014. In addition, the DEN is continuing its policy of encouraging researchers to obtain authorisation to supervise university research (HDR). Nine new HDR accreditations were obtained in 2015, bringing the total number of accredited researchers at the DEN to 113, to which 19 PhDs must also be added.

(1) This effect contributes to ensuring a nuclear reactor remains stable, by reducing its core reactivity when its temperature rises.

EXPERTISE AT THE DEN

THE EXPERTS PROGRAMME

The CEA has been running its experts programme since 2009, the aim of which is to increase the visibility of its top level scientists. The DEN currently has 72 level 4 experts (research directors and international experts) and 274 senior experts. These experts are scientific advisors in their fields. They are called upon when necessary to respond to specific requests from within the organisation, and they help to increase the standing of the DEN outside the CEA.

Conducting experiments to study the interaction of corium and concrete.

TECHNOLOGY WATCH

The DEN has monitored the literature in order to create a database on the following topics: water reactor technology, extraction chemistry, analytical chemistry, steels under irradiation, decontamination, high-temperature treatment, treatment of effluent, SFR technology, safety of reactors and pools, and numerical simulation applied to neutronics.

SCIENTIFIC SEMINARS

The Scientific Division regularly organises seminars to provide information on important scientific questions for the DEN and its research strategy in order to guide future research choices. In 2015, six topics were discussed:

- Understanding selectivity in separation chemistry;
- MOX fuel specifications for the first cores of Astrid, the SFR demonstrator;
- The potential of microsystems for research on the back-end of the nuclear fuel cycle;
- Possible specifications and technologies to enhance accident-tolerant characteristics of pressurised water reactor (PWR) fuels;
- The design of the core catcher for Astrid;
- The concept of an enhanced Doppler effect[1] core.

Four other scientific seminars were organised under the aegis of the CEA/EDF/AREVA institute, in the following fields:

- Ageing of steel in PWRs;
- More robust PWR fuels in the event of an accident;
- Control of the in- or ex-vessel corium in the event of a severe accident;
- Review of the safety baseline for analysing loss-of-coolant accidents (LOCA).

Hydrometallurgy-based separation chemistry being used to recycle strategic metals.

INVOLVEMENT IN THE ANCRE

The DEN is actively involved in the work of the French national alliance for energy research coordination (ANCRE), mainly through its Scientific Division's leadership of the "Nuclear energy" group. In 2015, following the organisation in Paris of the 21st session of the Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change, the ANCRE decided to conduct its own study into «decarbonisation levers» in the context of an international project aiming to draw up national decarbonisation pathways that are compatible with achieving the 2°C global warming limit by the year 2050. The group also conducted a foresight study into French industry's needs for heat within a 100 km perimeter around the nuclear power plants, which are likely to be covered by cogeneration. It opens up prospects which sound quite interesting in principle, and their economic viability needs to be confirmed.

MISSIONS INITIATED BY THE HIGH COMMISSIONER FOR ATOMIC ENERGY

As part of a mission sponsored by the High Commissioner for Atomic Energy, a number of experts contributed in 2015 to an analysis of the neutronic and thermal-hydraulic computer codes developed by the DEN. The resulting trends involve strengthening the place of computing and managing uncertainty in these codes, and also the use of fluid dynamics calculations to simulate reactor thermal-hydraulics numerically.

NUCLEAR EDUCATION AND TRAINING

The DEN passes on the knowledge and expertise it has developed by making a significant contribution to education in nuclear science and associated technologies, mainly in France but also through international training courses. This contribution focuses mainly on strategic training courses at fifteen or so higher education establishments at the Paris-Saclay University and more widely in the Île-de-France region, and at Académies in the Montpellier, Grenoble and Aix-Marseille regions, as well as north-west France. In 2015, some 500 of the DEN's staff delivered almost 10,000 hours of training, the majority of which was for the National Institute for Nuclear Science and Technology (INSTN): three-quarters involved degree courses, while one-quarter was for vocational training. Major highlights of 2015 were the introduction of a Masters course at the Paris-Saclay University, and the mentoring of five students, together with an offer of internships at the DEN, from the first intake of the Franco-Chinese nuclear power institute (IFCEN) at the end of their course.

Visit by a Chinese delegation to the Tamaris experimental platform at Saclay.

THE DEN ON THE INTERNATIONAL STAGE

The DEN cooperates with most major nuclear powers. Such cooperation concerns issues of national interest when requested by the Government, which can encourage the establishment of strategic partnerships with other countries that cover nuclear matters; scientific or technical issues, when international cooperation needs to be established in areas of expertise which complement those of the DEN; economic issues, when the DEN wishes to offer its services to foreign industrial partners, or is looking for foreign involvement in its investment in research infrastructures.

Cooperation has been particularly dynamic as concerns Generation IV sodium-cooled fast reactors (SFRs), large R&D infrastructures, and not forgetting dismantling and clean-up phases, with the work done and to be done at the Fukushima-Daiichi nuclear power plant.

CHINA

Cooperation with China involves working with associated laboratories. Three topics are the subject of dynamic cooperation: SFRs (China is also committed to projects using this technology), ageing of materials and safety of PWRs (hydrogen risk). This cooperation is due to intensify in the field of the back-end of the fuel cycle with the prospect of AREVA's sale of a spent fuel reprocessing plant to the China National Nuclear Corporation (CNNC).

UNITED STATES

The agreement with the US Department of Energy (DOE) was renewed in 2012. It involves several highly active working groups on neutronics and safety (especially in relation to the Astrid project), separation, advanced fuels and simulation. Cooperation around Astrid could be strengthened by the use of American facilities to qualify in-sodium components.

GREAT BRITAIN

Great Britain's decision to relaunch its nuclear programme has boosted cooperation. The British National Nuclear Laboratory (NNL) has acquired a 2% share in the JHR international consortium. In March 2016, it also signed a letter of intent with the CEA, outlining several potential areas of cooperation: optimisation and pooling of facilities, clean-up and dismantling, and developing the nuclear systems of the future. Alongside this letter of intent, Astrid is the subject of a special agreement including detailed technical aspects.

JAPAN

Relations with Japan are based around two main topics: the Astrid programme and clean-up/dismantling of the Fukushima Daiichi NPP. As concerns Astrid, Japan has expressed its interest in significantly expanding the topics it is working on, both in terms of R&D and design. New areas of cooperation, which could lead to improved design proposals and use of the Japanese Atomic Energy Agency (JAEA)'s facilities for experimental programmes, are under discussion. With regard to clean-up/dismantling of the Fukushima-Daiichi NPP, in 2015 the CEA signed two Memorandums of Understanding (MoU), firstly with the Nuclear Damage compensation and decommissioning Facilitation corporation (NDF), which established the roadmap for dismantling the NPP, and secondly with TEPCO, which is interested in special dismantling techniques.

RUSSIA

Cooperation with Russia, which was resumed in 2010, is focused on the development of SFRs. It primarily concerns R&D on Astrid: use of Russian irradiation resources and the BFS mock-up during the CEA's Masurca critical mock-up refurbishment works, plus a feasibility study for irradiation of an Astrid prototype fuel in the BN-600 reactor.

INDIA

Very clearly defined cooperation, limited to fundamental research and safety, allows the DEN to discuss SFRs amongst other things. The other aspect of cooperation concerns the JHR project, in which India has acquired a 2% share, and in-kind collaboration (development of Cloé, an irradiation loop for studying corrosion). India has also expressed its interest in involvement in the Plinius-2 project, an experimental platform for testing the behaviour of corium in various configurations.

CENTRAL EUROPE

A consortium called V4G4 consisting of Hungary, Slovakia, the Czech Republic and Poland was set up in 2013. Its aim was to build up new nuclear R&D skills for Generation IV reactors, especially gas-cooled fast reactors, and to coordinate the effort of the four institutes involved (each will host one specialist topic) in order to form a nuclear R&D centre in central Europe. The Allegro project is being formally steered via this consortium as of mid-2015. At present, the DEN is contributing to it with advice, and is assisting the discussions of the V4G4 consortium concerning the preliminary stage of defining a robust R&D programme, and the initial stage of a roadmap for the Allegro's design and safety. The CEA is considering formalising its status as an associated member of the V4G4 consortium.

EUROPEAN COMMUNITY

The DEN plays a very active role in governance of the European Sustainable Nuclear Energy Technology Platform (SNETP) which is dedicated to nuclear fission, and in its technical pillars: ESNII (European Sustainable Nuclear Industrial Initiative) concerning sustainable Generation IV nuclear technology, and NUGENIA (an R&D initiative concerning Generation II and Generation III reactors). Efforts to obtain finance from Europe, directed towards European projects of interest to the DEN, in the context of the Euratom work programme, are also being pursued. Other European partnerships have been formed on the fringes of the strictly community-based framework. In 2015 for example, cooperation agreements were signed with Switzerland (PSI), Germany (KIT and HZDR) and Italy (ENEA), in the context of the ARDECO project (Astrid R&D European Cooperation) concerning Astrid.

MULTILATERAL INITIATIVES

The CEA centres of Saclay and Cadarache have been certified «ICERR» (International Centre based on Research Reactors) by the International Atomic Energy Agency (IAEA). This certification will allow the CEA to enhance the international visibility of its certified installations (JHR and its associated facilities: Isis, Orphée, Léci, Eole-Minerve, and Leca-Star), and to boost its attractiveness, especially to countries wishing to set up a nuclear power programme, acquire technical capabilities and train their researchers.

In addition to participating in the Generation IV International Forum (GIF), of which it is one of the founding members and which the CEA Director of Nuclear Energy is chairing from 2016 to 2019, the DEN is actively participating in the NI2050 initiative of the OECD's Nuclear Energy Agency (NEA/OECD). This concerns the definition of international R&D programmes supporting appropriate nuclear power expansion in order to establish a world's low-carbon energy mix, in accordance with the International Atomic Energy Agency's 2-degree Celsius scenario (930 GWe by the year 2050).

Yukiya Amano, Managing Director of the IAEA (right), presents the ICERR certificates to Daniel Verwaerde, the CEA Chairman (left).

Séturiden day at Marcoule: discussions and awareness-raising concerning safety.

QUALITY, SAFETY AND ENVIRONMENT MANAGEMENT AT THE DEN

The DEN is firmly committed to quality-driven management of its activities. It has set up a dedicated organisation, consistent with its operational structure, to streamline its procedures and continually improve its management efficiency, while developing cross-disciplinary activities and ensuring that best practice is widely used on all sites where the DEN operates.
Its management system's triple quality, safety and environment (QSE) certification, obtained in 2013, was confirmed in 2015.

QUALITY-DRIVEN MANAGEMENT

Since its creation, the DEN has implemented numerous tools in order to assess its performance in terms of its main objectives. One example of this is the use of milestones, important dates during a project which usually concern a concrete achievement such as the production of deliverables. In 2015, more than 95% of milestones were achieved, demonstrating the importance the DEN places on adherence to project deadlines.

SAFETY OF PEOPLE

The DEN has implemented a policy to protect its workers which aims to establish and maintain a safety culture in both its teams and the suppliers who work in its facilities.

The number of work-related accidents in 2015 remained at the same level as in 2014 for CEA staff and for contractors. Travel and accidents described as non-work-related still account for the majority of absences. We deeply regret the death in September of an employee of an external contractor who was working on a civil engineering worksite in Marcoule. An enquiry is still ongoing to determine exactly what happened.

Raising awareness represents an essential part of the safety culture. This is why the DEN organises a "Sécuriden" day each year at the centres where it is present, to raise awareness of safety in staff, i.e. CEA employees and external contractors. This event was held on 3 November and focused primarily on vigilance vis-a-vis hazardous situations, crisis management, recognising electrical hazards in everyday situations, and training of new recruits. Conferences with external participants, scenarios illustrating situations likely to cause accidents or problems, and workshops within the facilities helped to raise employees' awareness of these risks.

Sécuriden day at Saclay: discussions and awareness-raising concerning safety.

ENVIRONMENTAL PROTECTION AND NUCLEAR SAFETY

The DEN has also implemented a policy to protect the environment, of which nuclear safety is a major component.

The number of significant events involving safety, radiation protection or the environment has increased on previous years. Nonetheless, only seven of these had a detectable impact on staff or the environment.

PROTECTION OF NUCLEAR MATERIALS

The DEN must ensure that the nuclear materials it uses in its R&D programmes are protected against theft and improper use. This protection is defined according to specific regulations which have recently been changed. Industrial companies which have such materials therefore have to review this protection by means of safety studies of their sites and facilities. In 2015, these were all upgraded in accordance with the predefined schedule.

MANAGEMENT OF CONFIDENTIALITY AND SECURITY OF INFORMATION SYSTEMS

Subject to the requirements for openness to international collaborations, respect of its industrial partners' confidentiality, and protection of its own scientific and technical assets, the DEN continued its confidentiality management action plan.

The DEN has also continued to implement the measures required to comply with the new regulations on the protection of French national scientific and technical potential.

THE DEN'S CONTRIBUTION TO NUCLEAR STANDARDISATION

It is essential that appropriate standards are drawn up for the design and construction of Generation IV nuclear systems.

The DEN is therefore carrying out a great deal of work in this area, with significant involvement of the R&D teams, in particular those working in the fields of materials and mechanical engineering.

The DEN has continued its support of the French Association for the rules governing the design, construction and in-service inspection of nuclear island components (AFCEN) in its policy of openness to other operators, manufacturers and research organisations, including those in other countries. It is still involved in this process in 2015 as it is chairing a *European Committee for Standardization* (CEN) workshop on behalf of the AFCEN. The objective of the workshop is to define the required adaptations of the codes for their potential users in Europe.

Samples of water, air and plants are regularly taken and analysed in the laboratory.

PROJECT MANAGEMENT AT THE DEN

The DEN runs all its programmes as projects and took the initiative in 2015 to improve how they are managed and implemented. To this end, it started to update the project management methods baseline by incorporating in it feedback from all projects since 2001, the year it was first set up. This baseline contains more than twenty operating documents, which make it possible for the various players to use the same methodology when managing performance, costs, timescales and risks. A number of guides included in this baseline have therefore been initiated in 2015 or are being prepared.

FOCUS ON

THREE SEMINARS TO PROMOTE THE USE OF THE PROJECT MANAGEMENT BASELINE

In 2015, the DEN started to roll out use of the project management methods baseline to the project players. Three seminars were therefore organised at each centre to promote its use and inform these players how its revision is progressing. More than 250 participants gathered for these seminars, which were followed by three training sessions so they could learn the basics of this tool.

Presentation of the *Decarbonization Wedges* report during the COP21.

Global 2015 International Conference.

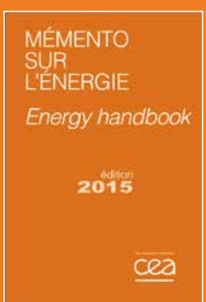
I-TÉSÉ

The Institute for Techno-Economics of Energy Systems (I-tésé) is conducting macroeconomic and microeconomic studies in support of CEA choices for R&D programmes.

FOCUS ON

PUBLICATION OF THE ELECNUC AND MÉMENTO ON ENERGY HANDBOOKS

As it does every year, I-tésé has written and published these two handbooks which summarise huge amounts of reference information relating to global energy, with a special focus on power generated by the nuclear fleet.



ACTIONS WITHIN THE SCOPE OF THE COP21

I-tésé was heavily involved in the COP21, which took place in Paris in December 2015. Ahead of this event, as a member of the French national alliance for energy research coordination (ANCRE), I-tésé helped organise one of the sessions at the scientific conference *Our Common Future Under Climate Change*, organised in Paris in July.

During the COP21, I-tésé played a key role at three events:

- Delivering to the French government the *Decarbonization Wedges* report, drawn up by ANCRE in association with the UN. This report especially analyses the potential of energy technologies to help us achieve France's climate objectives, and the "showstoppers" to be overcome by the year 2050;
- Participating in a presentation of this study at a conference fringe event;
- Coordinating a presentation on the role of hydrogen, also at a conference fringe event.

CONTRIBUTION TO THE NEA AND THE IEA'S REPORT ON THE ESTIMATED COSTS OF ELECTRICITY GENERATION

At the end of 2015 the International Energy Agency (IEA) and the Nuclear Energy Agency (NEA) published their benchmark study on the costs of electricity. The CEA teams, and especially those from I-tésé, worked closely with industry and the General Directorate for Energy and the Climate on this study. I-tésé's contribution mainly concerned supplying the French data, in particular obtaining a unique data set for the various industry sectors, as well as questions concerning methodology. An important result of this report has been to highlight that despite a significant drop in the costs of solar PV, the new nuclear is still just as competitive in OECD countries as a method of low-carbon electricity generation.

I-TÉSÉ'S PARTICIPATION AT INTERNATIONAL AND NATIONAL EVENTS

In September 2015, I-tésé attended the Global 2015 International Conference dedicated to the fuel cycle, in Paris. I-tésé organised a session at this conference on the economic challenges facing the nuclear industry and coordinated the scientific committee for this topic.

In 2015, during meetings organised on the topic of uranium at the IAEA, I-tésé presented a method for estimating the quantity of uranium resources in the world.

I-tésé has also organised several events for the French Nuclear Energy Society (SFEN): a conference on nuclear's place in global energy scenarios as far as the year 2050 and a day dedicated to the methodology for estimating dismantling costs.

7TH I-TÉSÉ SYMPOSIUM

The 7th annual I-tésé symposium took place on 17 June 2015. It discussed the place of hydrogen in energy transition and brought together 150 participants. Among the highlights of this day, we will remember the discussion on the role of hydrogen in energy transition with special guest speaker Laurent Kalinowski, French MP and member of the French Parliamentary Office for Scientific and Technological Assessment (OPECST).

Photo credits: Saveau/Ingerop ; AREVA/Larrayadieu Eric ; S. Le Couster/CEA ; P.Allard/REA/CEA ;
G. Lesénéchal/CEA ; P. Stroppa/CEA ; PF. Grosjean/CEA ; F.N'Guyen/CEA ; L. Godart/CEA ; AIEA ;
O. Metzger. ; Stéphane Reboul/CEA ; EDF/Christel Sasso ; ONET Technologies ; SFEN ;

Design and production: Obea communication .
This report is printed on paper from sustainably managed forests.

IMPRIM'VERT®

FROM RESEARCH TO INDUSTRY

Nuclear energy Division
CEA Saclay Centre
91191 Gif-sur-Yvette Cedex

www.cea.fr

Communication contact: alexandra.bender@cea.fr