R&D ACTIVITIES OF THE SPANISH RESEARCH INSTITUTIONS AND UNIVERSITIES ON GEN IV REACTORS AND ADVANCED NUCLEAR SYSTEMS

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The sustainability of nuclear energy has driven the development of the Generation IV (Gen IV) reactors and advanced nuclear systems that are extremely safe, economically competitive, extend the use of resources, minimise the waste and obey strict non-proliferation requirements. The deployment of the advanced systems and Gen IV reactors requires extensive national and international coordinated R&D programs. In Spain, this R&D is carried out in the public sector by CIEMAT, the Universidad Politécnica de Madrid and Universitat Politècnica de València and also by the solid Spanish nuclear industry. The activities are being funded by ENRESA, EURATOM and the Spanish Ministry of Economy, Industry and Competitiveness R&D programs and can be grouped in four large areas: reactor design, safety, materials and fuel cycles.

ACTIVIDADES DE I + D SOBRE REACTORES GEN IV Y SISTEMAS NUCLEARES AVANZADOS EN LAS INSTITUCIONES DE INVESTIGACIÓN Y UNIVERSIDADES ESPAÑOLAS

La sostenibilidad de la energía nuclear ha motivado el desarrollo de reactores de Generación IV y sistemas nucleares avanzados que son altamente seguros, competitivos económicamente, que extienden la vida de los recursos naturales, minimizan la producción de residuos y obedecen a criterios muy estrictos de no proliferación. La implantación de los sistemas avanzados y de Gen IV requiere aún importantes esfuerzos de I+D materializados en programas coordinados internacionalmente. En España, dicha I+D es realizada a nivel público por el CIEMAT, la Universidad Politécnica de Madrid y la Universitat Politècnica de València y, a nivel privado, por la potente industria nuclear española. Las actividades de I+D están siendo financiadas principalmente por ENRESA, EURATOM y el Ministerio de Economía, Industria y Competitividad y pueden agruparse en cuatro grandes áreas: diseño de reactores, seguridad, materiales y ciclos de combustible.

INTRODUCTION

In recent years, small modular reactors (SMR) have attracted attention because they can meet the needs of emerging electricity markets. They use a proven technology together with novel designs, including new engineering solutions relying on passive features. Passive safety features do not require outside power input to work, instead depending only on physical laws.

The sustainability of nuclear power depends upon deploying systems that are extremely safe, economically competitive, capable of significantly extending uranium resources for centuries, and minimising waste while simultaneously easing proliferation concerns. These goals have driven the development of the Generation IV reactors and advanced nuclear systems.

The deployment of the future reactors requires extensive international R&D programs on:

- New reactor technologies like Liquid Metal Fast Reactors (LMFR), Gas Cooled Reactors (GCR) and Accelerator Driven subcritical Systems (ADS) for the efficient management of the nuclear waste.
- Fuel cycle technologies related to the reprocessing of irradiated fuel, fabrication of new fuels, advanced waste management and disposal.

The R&D in the field is mainly driven by national and international programmes and coordinated at international level by different stakeholders such as the Generation IV International Forum (GIF), the International Atomic Energy Agency (IAEA) or the OECD/Nuclear Energy Agency (NEA). In Europe, the R&D is funded by national programmes from the member states and the EURATOM programme [1] within H2020, which follows the directives given in the Strategic Energy Technology (SET) Plan, aiming at accelerating the development and deployment of low-carbon technologies. Furthermore, the independent Sustainable Nuclear Energy Technology Platform (SNETP) has established a Strategic Research Agenda and a Deployment Strategy to ensure that fission energy is generated in a manner that meets the criteria for sustainable development in strict compliance with the safety requirements. The European Sustainable Nuclear Industrial Initiative (ESNII) is the one of three SNETP pillars for demonstrating Generation IV Fast Neutron Reactor technologies, together with supporting research infrastructures, fuel facilities and R&D work.

R&D ACTIVITIES IN SPAIN

As it is natural in a country producing about 20% of its electricity in nuclear reactors, Spain counts with an important nuclear industry. Spain does not belong to the GIF but several engineering companies have participated in various European R&D projects linked to Gen IV or are following the activities in Gen IV in international forums like ESNII. Among them, one could highlight i.a.o. ACCIONA, ADEX, Empresarios Agrupados, ENDESA, ENSA, Gas Natural Fenosa, Iberdrola, IDOM, SENER and Tecnatom. In the public sector the R&D is carried out by CIEMAT, the Universidad Politécnica de Madrid (UPM) and Universitat Politècnica de València (UPV) through the participation in international R&D

programs on the development of Gen IV reactors and related fuel cycle technologies. The Spanish R&D in Gen IV and advanced nuclear systems can be grouped in four large areas: reactor design, safety, materials and fuel cycles. These activities have been funded by ENRESA, EURATOM and the Spanish Ministry of Economy, Industry and Competitiveness R&D programs.

REACTOR DESIGN

The Spanish R&D activities related to reactor design focus on three areas:

Core design

The R&D in core design is mainly related to the development of two ESNII demonstrator facilities: MYRRHA (lead-bismuth cooled, Multi-purpose hYbrid Research Reactor for High-tech Applications coupled to an external accelerator, Figure 1), and ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstrations). Both MYRRHA and ASTRID should be put in operation in the next decades. Minor efforts are also dedicated to the two other ESNII demonstrators, ALFRED (Advanced Lead Fast Reactor European Demonstrator) and ALLEGRO (a gas cooled fast reactor demonstrator), also part of the ESNII roadmap.

As part of EURATOM projects, the Nuclear Innovation Unit of CIEMAT and UPM have carried out extensive research in core design and safety analysis of both demonstrators and industrial concepts of fast critical reactors and advanced nuclear systems. The most relevant projects are:

- ESNII-PLUS of the 7th European Commission Framework Programme (EC FP) [2]: the activities performed have been related to criticality analysis, evaluation of reactivity parameters such as Doppler coefficient, void worth, and control rod worth, power mapping and possible re-criticality of the molten pool after a severe accident. Uncertainties quantification from manufacturing tolerances and nuclear data have also been performed [3].
- CP-ESFR [4] of the 7th EC FP: Activities were focused on the neutronic optimization of the European sodium cooled fast reactor (ESFR) core (introduction of sodium plenum and blankets, among others) and the analysis of the potential of different configurations for minor actinide transmutation. UPV has developed a methodology to perform transient analysis for sodium-cooled reactors using TRACE and PARCS codes.
- CDT-FASTEF [5] of the 7th EC FP: Activities consisted in the evaluation of criticality and reactivity safety parameters, neutronic optimization for increasing the fast neutron flux, and analysis of some critical and subcritical configurations.
- MTR+I3 [6] of the 6th EC FP, with the study of the behaviour of the neutron flux using shielding materials.
- EUROTRANS [7] of the 6th EC FP: the activities were focused on the design and neutronic characterization of XT-ADS and EFIT (demonstrators for dedicated transmutation of nuclear waste).
- RED-IMPACT [8] of the 5th EC FP, with the analysis of the transmutation potential of sodium fast reactors and dedicated subcritical systems.

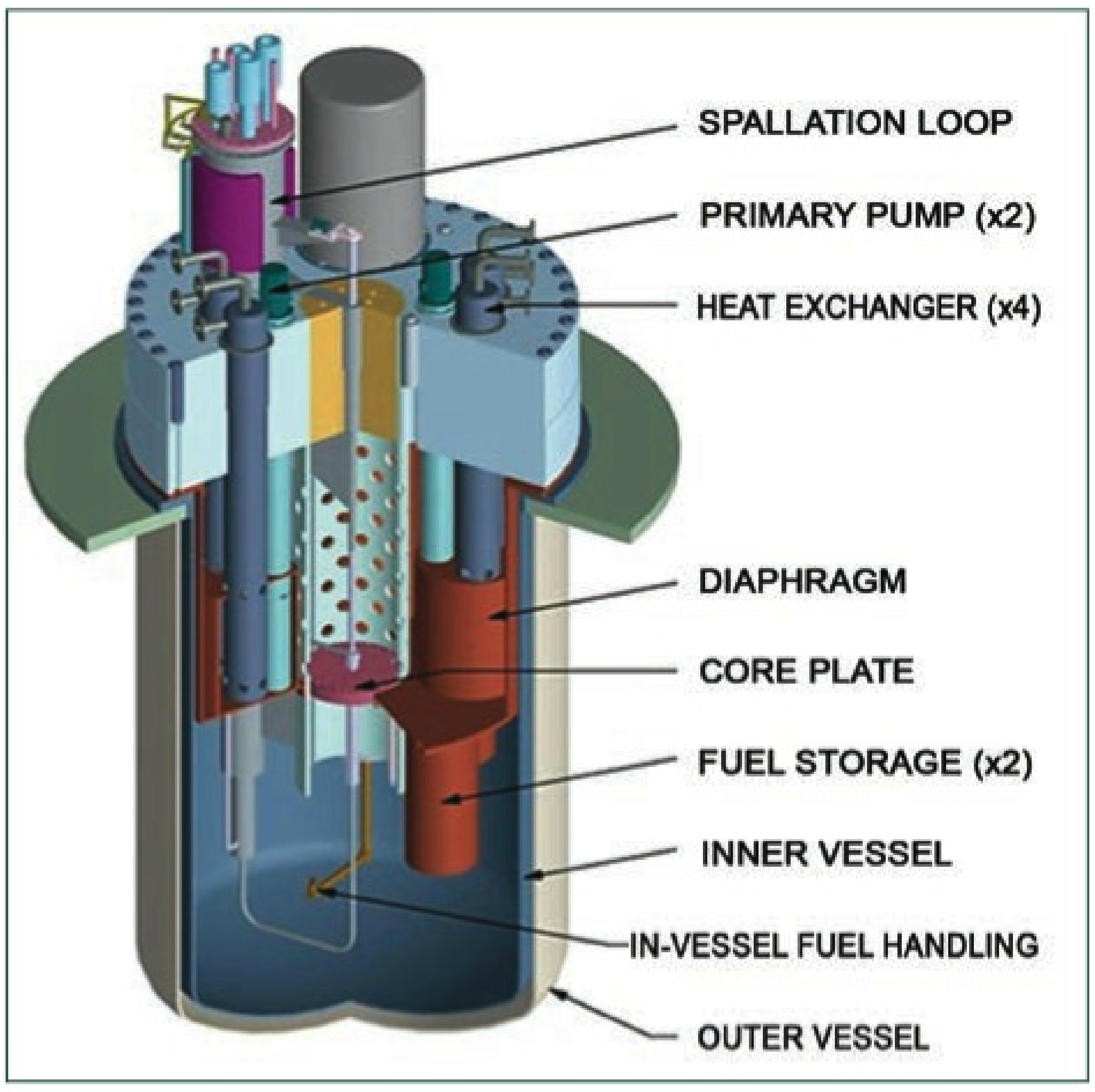

Figure 1. Conceptual design of the MYRRHA reactor. Source: SCK·CEN.

Among the advanced nuclear systems dedicated to particular applications such as transmutation, one of most promising concepts is the accelerator-driven subcritical system (ADS). The industrial versions of ADS are currently in the conceptual design phase and MYRRHA (Figure 1), in its subcritical mode, will be a demonstrator of this technology. CIEMAT is centred mainly in core design of MYRRHA within the 7th EC FP MAXSIMA [9] and ARCAS [10] projects, the completed CDT-FASTEF and EUROTRANS EC projects, and also in the frame of dedicated Coordinated Research Projects of the IAEA.

Code development and nuclear data

The design of Gen IV and advanced nuclear systems requires the use of powerful computational tools that in turn make use of nuclear data. CIEMAT, in addition to using the most advanced Monte Carlo simulation codes (such as MCNP, SCALE, GEANT4, etc.) and evaluated nuclear data libraries (such as JEFF3.2 and ENDF/B-VII.1) available, has developed over the last decade its own codes for addressing specific applications: EVOLCODE for the description of the reactor evolution [11], TR_EVOL for fuel cycle analyses [12], and COUNTHER, a coupled neutronics – thermal hydraulics code for the analysis of transients [13].

The quality of the nuclear data is crucial for meeting the design requests. Of particular importance are neutron cross section data of minor actinides in the fast neutron energy range, which are more relevant in advanced reactors than in Light Water Reactors (LWR). CIEMAT is carrying a scientific program on the systematic measurement of neutron induced reaction cross sections of minor actinides at the CERN n_TOF neutron spallation source [14] with the support of ENRESA, the Spanish National R&D plan and various EURATOM projects like the on-going CHANDA [15] project. Besides, CIEMAT and UPM participate in various international groups of experts from the IAEA and OECD/NEA in the evaluation, verification and validation of nuclear data [16].

Integral experiments

Integral experiments are carried out in zero-power reactor mock-ups, and are aimed at validating nuclear design tools and reactor concepts before the construction of power reactors. CIEMAT has a long history of participation in integral experiments for ADS and Gen IV reactors in Europe. It began with the MUSE-4 experiment (5th EC FP) at the MASURCA reactor in CEA – Cadarache, a mock-up of a sodium fast reactor. Later, CIEMAT led the experimental campaign performed within the EUROTRANS project (6th EC FP) at the YALINA-Booster subcritical assembly of the Belarusian Academy of Sciences. More recently, CIEMAT has led several tasks of the FREYA project (7th EC FP), that consists in integral experiments at the VENUS-F reactor of the Belgian SCK-CEN, a mock-up of a lead fast reactor (Figure 2). These experiments are being continued under the MYRTE (H2020) project, now aimed at simulating MYRRHA cores in the VENUS-F reactor. In addition to the validation of codes and nuclear data libraries, CIEMAT's activities in these projects are focused on the development of subcriticality monitoring techniques for their use in ADS (Figure 3).

SAFETY

The Spanish R&D activities related to reactor safety focus on two areas:

Previous to the activities to be described in the coming section, the Unit of Nuclear Safety Research of CIEMAT participated in the RAPHAEL project (5th FWP of EURATOM) and CP-ESFR project (6th FWP of EURATOM). In the former, their contribution concerned activities related to the transport of radionuclides and graphite powder across the primary system and containment; whereas in the latter they built a Phenomena Identification Ranking Table concerning source term in case of Beyond Design Basis Accidents (BDBA), from which research needs were derived and major differences with LWR Source Terms were set. All this work was reported at the time in the open international literature (beyond the scope of the most recent work reported in next section).

Model Development for the ASTEC-Na Code

The extremely demanding safety goals set for Gen IV nuclear systems are driving the development of analytical tools capable of modelling the entire system behaviour from normal operation to the most severe accident imaginable. CIEMAT, through the participation of the Unit for Nuclear Safety Research in the SFR-focused JASMIN project (7th FWP of EURATOM), has collaborated in this venture by contributing to the development and validation of models that will be eventually integrated in the so-called

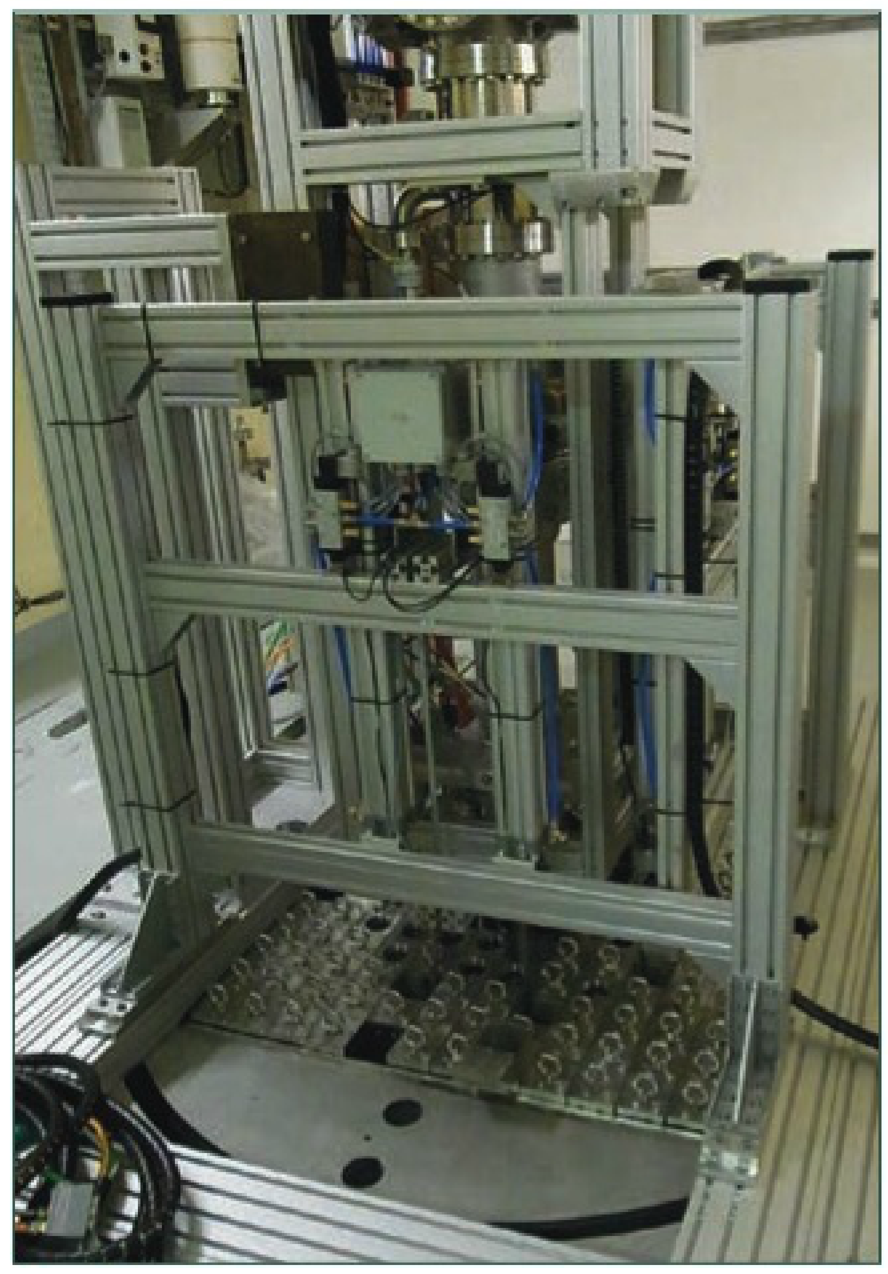

Figure 2. Photograph of a configuration of the VENUS-F reactor as an ADS investigated during the FREYA experiments. The reactor core with the fuel elements can be seen in the lower part. The structures above are the coupling structures for the accelerator driven external neutron source (Copyright © 2016 – SCK·CEN).

ASTEC-Na code [18], an analytical severe accident tool developed by IRSN and GRS. The work has been framed in the areas of Fuel pin Thermo-Mechanics and Source Term and the specific models developed concerned yield strength and strain limit of 20% CW 316 SS cladding under transient conditions and particle generation during Na pool fires.

Based on a critical review of available data and correlations of yield strength and the strain limit of 20% CW 316 stainless steel, a set of empirical correlations have been proposed that turned out to capture the experimental trends observed on the conservative side and to be more accurate than previously existing models, despite being notably simpler. In the case of yield strength, σ_y, a sigmoidal function was derived for the temperature, T, and neutron fluence, ϕ_t, validity ranges of 811-1144 K and 0-4.4·10^{26} n/m^2, respectively [19]:

$$\sigma_y = \frac{g_1(T)}{1+\left[g_2(T)\cdot\varepsilon\right]^{-g_3(T)}} + \frac{a_{IH}.(\sigma_s-\sigma_{y0})}{1+\left(\dfrac{\phi\cdot t}{b_{IH}}\right)^{-c_{IH}}}$$

with

$$g_i(T) = a_i \cdot \exp(b_i / T)$$

Nonetheless, the most relevant conclusion achieved in the study was the substantial lack in the open literature of data under foreseen conditions, so that a database enlargement is pointed at as one of the main future challenges for research in this area, not just for the material here addressed but also for other alternatives, like 15-15 Ti.

Beyond failure of fuel pins during transients, under postulated Beyond Design Basis Accidents (BDBA) potential sodium discharge in the containment would have major consequences for accident development in terms of energetics and source term. Sodium vaporization and subsequent oxidation would result in supersaturated oxide vapours that would undergo rapid nucleation creating toxic

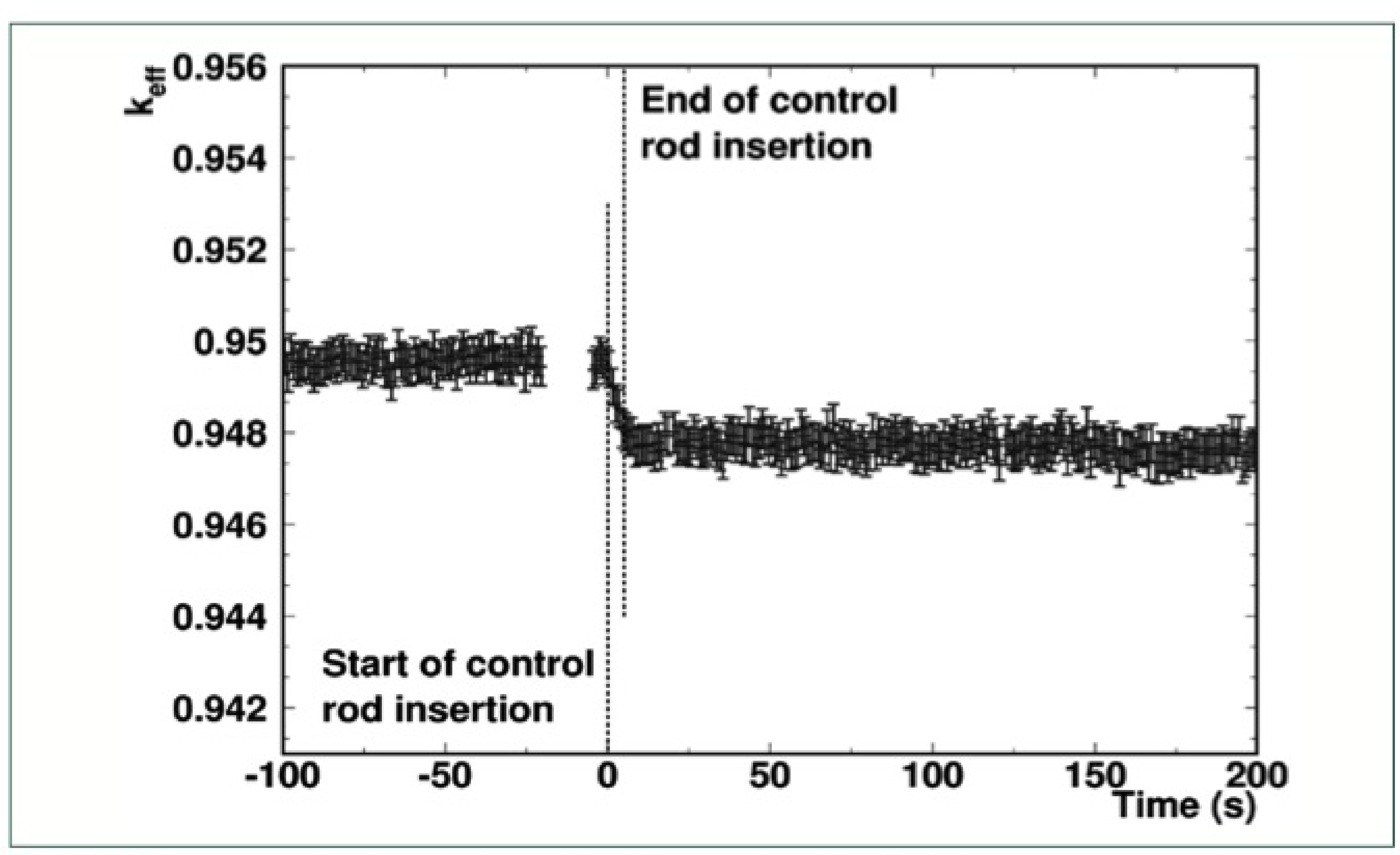

Figure 3. Measured values of the criticality constant (keff) of the YALINA-Booster subcritical assembly during a control rod insertion [17].

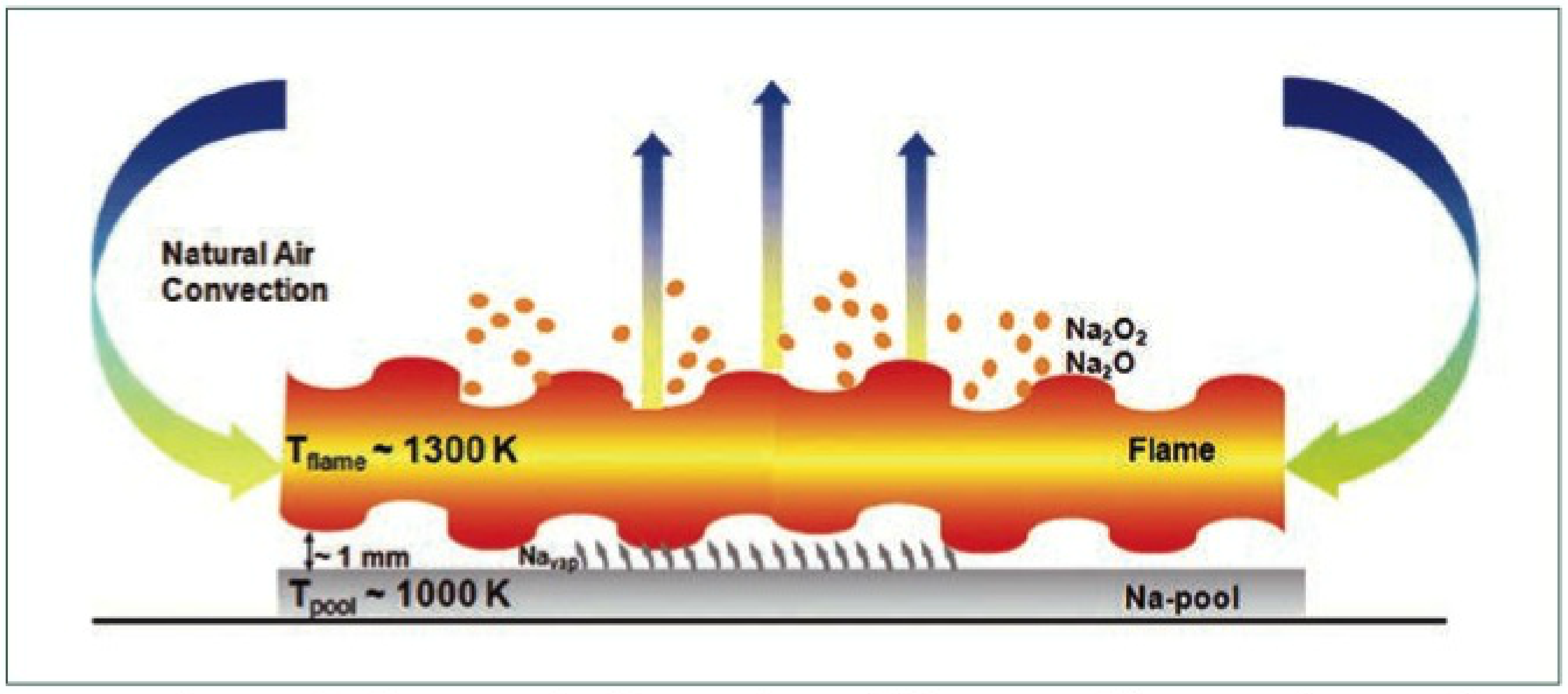

Figure 4. Conceptual approach of CIEMAT's model for Na-pool fire aerosol generation.

aerosols (Figure 4). A particle generation model to calculate the particle generation rate and their primary size during an in-containment sodium pool fire has been developed. Based on a suite of individual models for sodium vaporization, oxygen natural circulation (3D modelling), sodium-oxygen chemical reactions, sodium-oxides-vapour nucleation and condensation, its consistency has been partially validated by comparing with available experimental data.

As an outcome, large temperature and vapour concentration gradients set over the sodium pool have been found which result in large particle concentrations in the close vicinity of the pool [20]. By calculating more than 150 scenarios a database has been set up. From it, a 0-D analytical correlation of total particle generation rate has been derived as a function of pool temperature, pool size and oxygen fraction in the gas atmosphere. As for particle size, the results obtained showed little sensitivity with boundary conditions, so that a constant primary particle diameter of around 10-9 m has been set.

The particle generation model, along with others, was implemented in the ASTEC-Na code. A peer review of earlier experimental investigations allowed collecting data on in-containment aerosol behaviour, so that the CPA* module of the code dealing with containment phenomena has been validated to some extent. A number of tests have been simulated (ABCOVE-AB1 and -AB2; FAUNA-F2; EMIS 10B) and the results of CPA* and other codes compared to data [21]. Figure 5 gives an example of such comparisons.

This work revealed that experimental trends can be roughly reproduced with a single-cell approach whenever natural convection is effective in making the vessel atmosphere uniform both thermally and in composition; however, the present heavy parameterization of ASTEC-Na models concerning both combustion energy distribution and aerosol formation/behaviour, makes predictions quite dependent on users' approximations, which is inconvenient in sight of the lack of empirically supported default values. Therefore, further specific experimentation has been recommended to enhance code validation and models robustness.

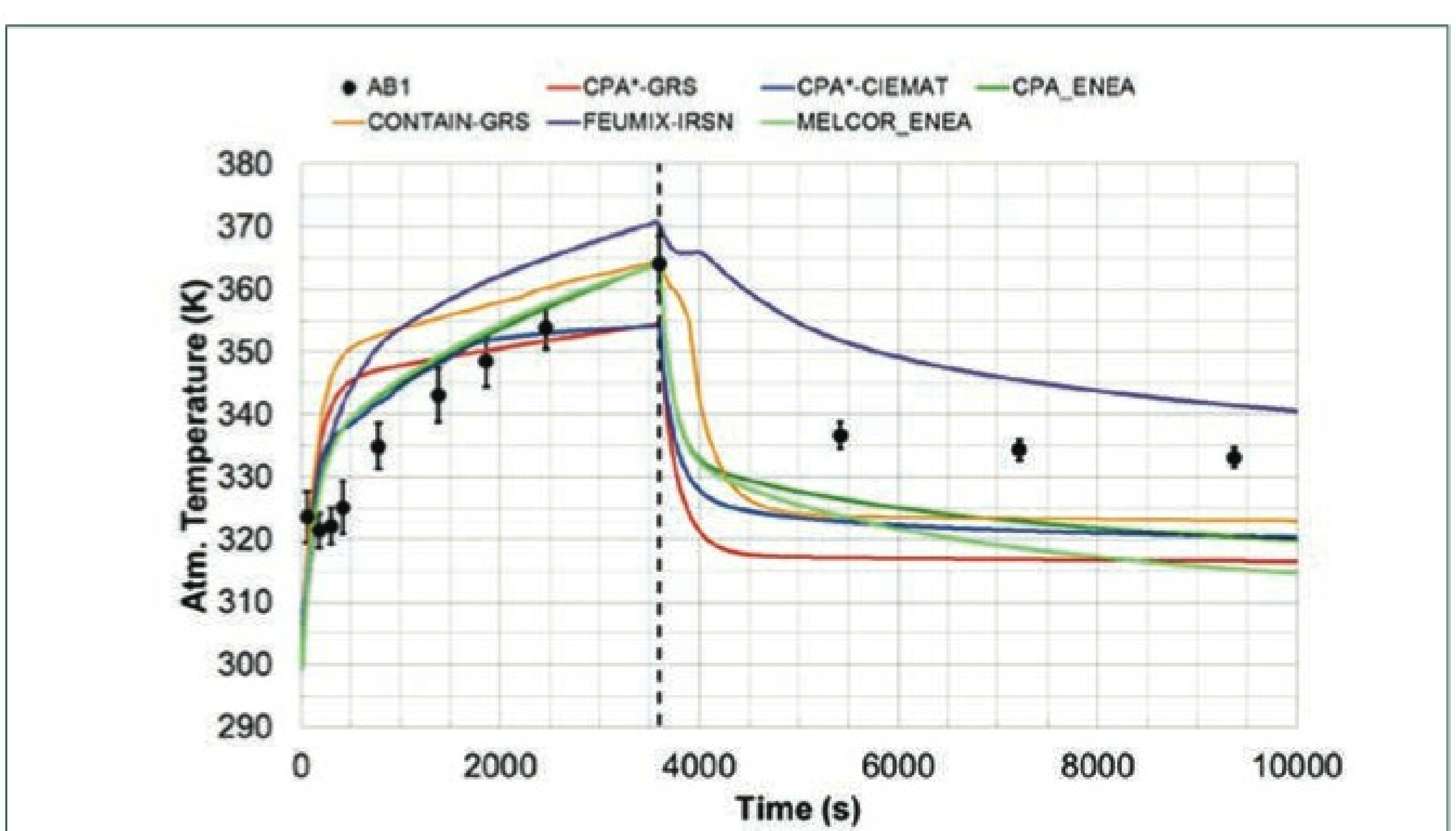

Figure 5. Atmosphere temperature (AB1).

Risk-informed safety analysis methodologies

With the objective of future assessment of the future advanced reactor concepts like ASTRID (SFR), ALFRED (LFR) and ALLEGRO (GFR), the SARGEN_IV Project of the 7th EC FP (Proposal for a harmonized European methodology for the safety assessment of innovative reactors with fast neutron spectrum to be built in Europe) was performed in order to:

- develop and provide a tentative commonly agreed methodology for the safety assessment,
- identify open issues in the safety area, mainly addressing and focussing on assessment relevant ones,
- detect and underline new fields for R&D in the safety area
- provide a roadmap and preliminary deployment plan for safety-related R&D, including cost estimation.

The UPM nuclear safety group (ETSII + ETSIME) has collaborated in several work packages and has performed the following tasks:

- Comparison of Technology Neutral Regulation approaches in risk-informed safety assessment: ISAM (IAEA); NUREG-1860 (NRC); ISA (CSN); MHTGR and PBMR safety assessment methodologies [22].
- Previous Experience in Design and Operation of Decay Heat Removal Systems in SFRs [23].
- Application of ISAM methodology to SFR: Implementation of the Defence In Depth for the Core Heat Removal in the SFR. Objective Provision Trees [23].

One new proposal related with these issues and with relevant Spanish contributions has been submitted to the last EURATOM H2020.

MATERIALS

The selection of suitable structural materials able to sustain the extreme operating conditions of Gen IV systems must be addressed and resolved to take full advantage of such innovative reactors. Structural materials will be exposed to higher irradiation dose (core materials), higher temperature in comparison to existing LWR, and in contact with non-aqueous coolants. Therefore, existing nuclear materials cannot in general be used or need specific qualification for those conditions. The difficulty is not only to select and qualify new materials but also to modify existing nuclear codes to include new design rules, mainly related to creep and creep-fatigue, and to include environmental effects. Austenitic stainless steels are the main candidates for both cladding and structural materials for the short term prototypes. Despite their limitations in terms of swelling resistance, the qualification of this class of materials and the previous experience in their use in past fast reactors programs make their choice the most appropriate. Ferritic/martensitic (F/M) steels, with higher swelling resistance than austenitic steels, are the best candidates in the medium and long-term, however some properties need to be improved, such as their poor compatibility with heavy liquid metals and their creep and fatigue softening behaviour. Improved materials like oxide dispersion strengthened (ODS) steels and ceramic composites for higher burn-up and higher temperature use are also investigated.

The European Energy Research Alliance (EERA) Joint Programme [24] on Nuclear Materials (JPNM) was launched in 2010 to provide the R&D for materials needed for the development and implementation of fast reactors in Europe, as defined by ESNII. The activities within the EERA JPNM are target two objectives:

1. Better knowledge of materials behaviour under operating conditions, seeking predictive capability, to select the most suited materials and define safe design rules, especially allowing for radiation and temperature effects, while caring for compatibility with coolants.
2. Development of innovative materials with superior capabilities, either through suitable processing methods applied to existing materials or adoption of new types of materials.

The EERA JPNM is divided in four sub-projects dealing with structural materials and two with the fuel:

- SP1: Materials for ESNII demonstrators and prototypes.
- SP2: Innovative high temperature resistant steels.
- SP3: Refractory materials: ceramic composites, cermets and metal-based alloys.
- SP4: Physical modelling and modelling-oriented experiments for structural materials.
- SP 5: Synthesis, irradiation and qualification of advanced fuels.
- SP 6: Physical modelling and separate effect experiments for fuels.

Most of the Spanish activities related to Gen IV materials are developed within the framework of the EERA JPNM. CIEMAT is the Spanish representative and member of the EERA JPNM Management Board as coordinator of SP2. In addition several institutions are associated to CIEMAT, such as: National Centre for Metallurgical Research (CENIM), International Centre in Critical Raw Materials for Industrial Technologies (ICCRAM), IMDEA, University of Alicante (UA), Polytechnic University of Catalonia (UPC).

From the period 2014-2017, most of the activities are included in the MatISSE Project [25], funded by the EC to support the EERA JPNM. Relevant Spanish contributions are related to the development and qualifications of ODS cladding tubes (CIEMAT), modelling of irradiation-induced hardening and creep in F/M steels (CIEMAT, UA) and Creep-fatigue of F/M and austenitic steels (CIEMAT). The contribution to the EERA JPNM in the period 2016-2020 is defined through the Pilot Projects. These are small projects focused on precise topics that result from the convergence of national research interests. The Spanish participation is related to the development of enhanced F/M steels (CIEMAT, CENIM), multiscale simulation of hardening and deformation mechanisms of F/M steels (CIEMAT, UA, UPC, IMDEA), liquid metal embrittlement (CIEMAT) and refractory materials (ICCRAM). Two new proposals, that include selected activities from the EERA JPNM Pilot projects, with relevant Spanish contributions, have been submitted to the last EURATOM H2020 call, one of them coordinated by CIEMAT.

The UPM is doing R&D for materials for fusion reactors and Gen IV in two areas: the understanding of the diffusion of defects in FeCr alloys and its dependence on the concentration of Cr, and the development of fabrication and characterisation methods of SiC samples for their irradiation.

NUCLEAR FUEL CYCLE

In the near future, it is foreseen that the nuclear fleet of a country or region will include reactors coming from different generations, having different technologies (thermal and fast reactors, together with their associated fuel cycle needs) and objectives (electricity generation, closed cycle for waste minimisation, etc.). R&D is required for optimizing the nuclear fuel cycle, which will include a mix of Gen IV and LWRs, offering solutions to the issues appearing in the transition from an open or partially closed fuel cycle to other fuel cycles with a long-term sustainability or involving a nuclear phase-out. The Nuclear Innovation Unit of CIEMAT is doing fuel cycle scenario studies framed in international collaborations, sharing different views and approaches to nuclear energy and producing a coherent vision:

- The OECD/NEA, whose latest major activities have been to verify the capabilities and results of the fuel cycle codes and to analyse the impact of the uncertainty in the input parameters on the fuel cycle indicators by means of a parametric analysis [12].
- The IAEA, in the INPRO initiative, assessing the benefits of sharing a final disposal in Europe [26].
- The evaluation of costs of Gen IV and ADS systems (ARCAS project) and different waste management strategies (RED-IMPACT).

For its part, the High Level Radiactive Waste Unit of CIEMAT addresses key R&D for the development of partitioning techniques and the safety assessment of the geological disposal of spent advanced nuclear fuels and high level waste. More specifically:

- Partitioning. Aqueous partitioning processes were developed up to scientific feasibility, through hot-tests. These processes involve new extracting or complexing organic molecules and industrial diluents that are being characterised [27]. Concerning pyrochemistry, CIEMAT has been involved on the recovery of MA from of metallic fuels and inert matrix transmutation targets. Results, experiences and knowledge gained in the previous reprocessing projects /programs (ACCEPT – 6th EC FP, SACSSES – 7th EC FP and GENIORS – H2020) have been used to modify and optimise the molten salt separation processes from the point of view of safety.

– Disposal. The development of robust safety cases for geological disposal of advanced nuclear fuels requires a solid understanding of their stability over very long timescales (up to a million years). CIEMAT is deeply involved in the EC (DISCO and GENIORS, H2020) and national programs (ENRESA) to study the spent advanced fuel dissolution as the main source term for the release of radionuclides under repository conditions, to assess both the expected long-term evolution of spent fuel repositories [28] as well as scenarios of early failure of the engineered barrier system [29].■

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