NUGENIA R&D ON SAFETY ISSUES - PERSPECTIVES IN THE DOMAINS OF AGEING AND OF SEVERE ACCIDENTS

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Abstract:
The key objective of the NUGENIA non-profit Association, created in 2011, is to proceed towards safer and economic long term operation of the Generation II&III nuclear power plants, particularly in Europe, by facilitating the cooperation for applied R&D within the European nuclear community. The Association has received the mandate from the Sustainable Nuclear Energy Technology Platform (SNETP) to act as the body in charge of coordinating at EU level this R&D implementation. The R&D roadmaps in eight technical areas are currently being elaborated, with short, mid and long term time-schedules.
Two of the areas strongly rely on the outcomes of successful networks of excellence that were launched in the frame of the Framework Programmes of the European Commission: NULIFE on safety-oriented research on materials, structures and systems, coordinated by VTT, and SARNET on research on reactor severe accidents, coordinated by IRSN.
The main conclusions of both networks on R&D issues to be addressed in the future are summarized in this paper for two domains: ageing of metallic components and severe accidents. They are the basis for the NUGENIA roadmap under elaboration and review.

1 INTRODUCTION

The Sustainable Nuclear Energy Technology Platform (SNETP) has been founded in 2007. Its vision identified among others that the nuclear fission sector must improve the safety and competitiveness of today's technologies. SNETP issued the Strategic Research Agenda (SRA) in 2009 and the Deployment Strategy (DS) in 2010. In 2011, the “Technological Working Group Gen.II-III” of SNETP and the EC network of excellence NULIFE [1] decided to join their R&D activities for the safe and economic long term operation of current and future Generation II and III reactors. NULIFE, coordinated by VTT, aimed at integrating safety-oriented research on materials, structures and systems and at exploiting the results of this integration through the production of harmonised life time assessment methods. This led to the creation in 2011 of the NUGENIA non-profit association. It received the SNETP mandate to act as the body in charge of coordinating at EU level the implementation of the R&D within Gen.II&III technical scope. More recently the SARNET network of excellence [2], coordinated by IRSN, has brought to NUGENIA its experience in the domain of reactor severe accidents, the importance of which has been underlined by the 2011 Fukushima-Daiichi accidents in Japan.

A key element in NUGENIA is the work of eight Technical Area groups, which serve to cluster relevant expertise and provide a focus for R&D activities. The R&D roadmaps in all technical areas are currently being elaborated, with short, mid and long term time-schedules. Two of the areas concern respectively: systems, structures and components, including materials ageing, based on NULIFE experience and coordinated by AREVA GmbH, and severe accidents, based on SARNET experience and coordinated by IRSN.

2 WHAT IS NUGENIA

2.1 SNETP and NUGENIA

In 2007 the European Commission issued its Strategic Energy Technology Plan (SET-Plan) outlining its main long-term objectives concerning energy production and supply. This essentially meant looking at sustainable development, security of supply and competitiveness. Technology platforms play a key role in the implementation of the SET-Plan for Research and Innovation. These platforms cover different technologies and energy sources, including nuclear energy, which represents a safe and proven technology for the production of low carbon energy at a competitive cost.

To meet the goals laid down in the SET-Plan for nuclear power production, SNETP was launched in late 2007 and includes now more than 150 member organizations of diverse types (industry, utilities, research, TSO, universities…). It is built on three pillars: current technology and its evolution (Gen.II & III), future technology (Gen.IV) and cogeneration of power and heat.

The former pillar led to the creation of the NUGENIA international non-profit association (www.nugenia.org) to provide a single framework for collaborative research and development of Gen.II and III nuclear power plants (NPP). It was founded under Belgian legislation in November 2011, and officially launched in March 2012. SNETP mandated NUGENIA on 1st April 2012 to act as the body in charge to coordinating at EU level the implementation of the R&D in the above technical scope. NUGENIA will liaise closely with existing external international organizations or entities (such as OECD/NEA, IAEA…), directly or through the SNETP.

In order to attain scientific and technical excellence, it is essential to integrate projects and expertise developed previously in European R&D projects such as networks of excellence, in particular NULIFE and SARNET. The integration of NULIFE has started a few years ago, as illustrated in the Figure 1 below.

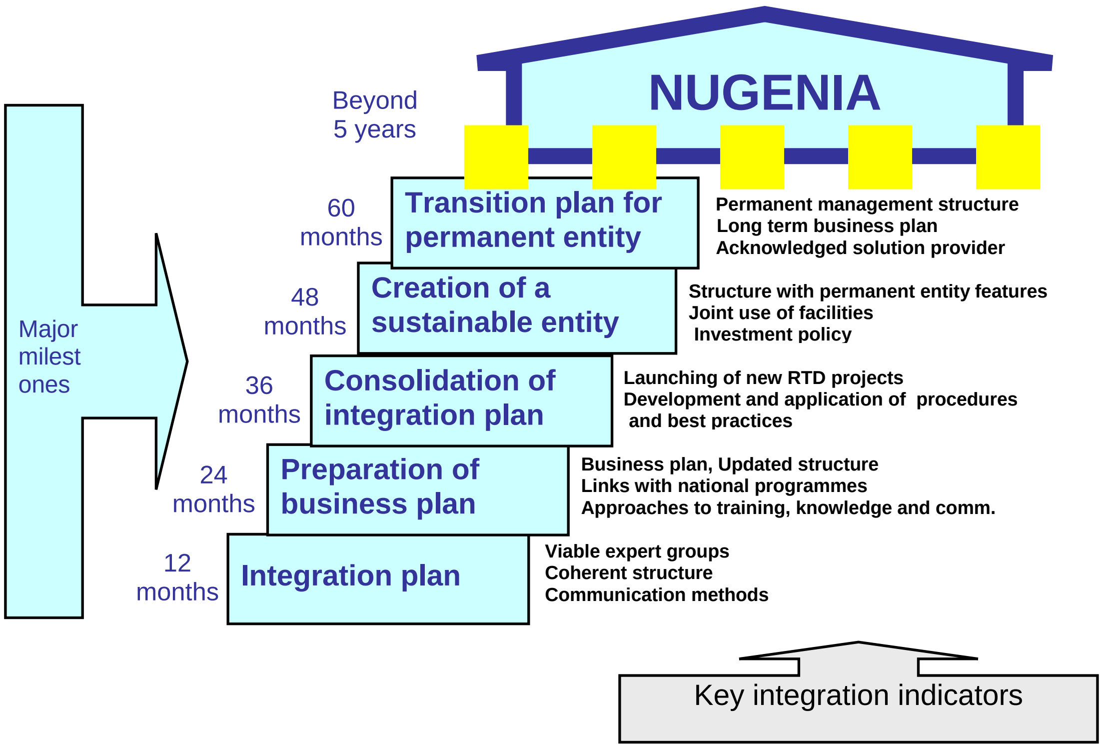

Figure 1: Progressive integration of NULIFE in NUGENIA [1]

NUGENIA members are major nuclear stakeholders: end of 2012, about 60 members in 20 countries, from industry, utilities, research institutions and technical safety organizations. JRC is an honorary member.

2.2 Structure and missions of NUGENIA

The main missions are to be the integrated framework between industry, research, safety organizations and universities for safe, reliable and competitive Gen.II & III fission (see Figure 2). The services will consist in:

- To run an open innovation marketplace,
- To promote the emergence of joint research,
- To facilitate the implementation and dissemination of R&D results.

Figure 2: NUGENIA integrated framework

And the products will be:

- R&D roadmap and portfolio of coordinated projects,
- Advanced scientific and technical base for Gen.II & III technology,
- Support to harmonization at European level, in particular for safety requirements.

The governance structure is shown in the following Figure 3:

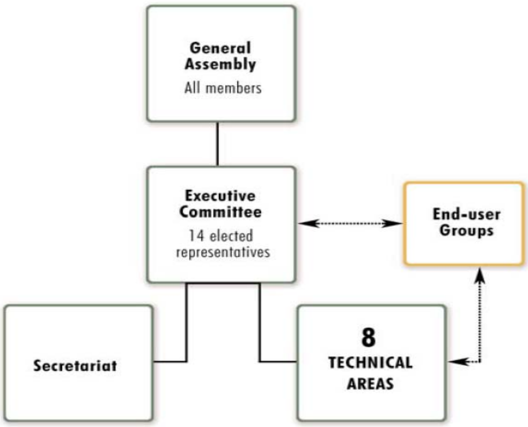

Figure 3: NUGENIA structure

Two end-users groups are defined: one gathering Technical Safety Organizations or TSOs, and one gathering organizations from nuclear industry and vendors.

Eight technical areas have been defined, each with a leader:

- Plant safety and risk (coordinated by G. Hultqvist, Vattenfall),
- Severe accidents (coordinated by J.-P. Van Dorsselaere, IRSN),
- Core and reactor operation (coordinated by G. Mariotti, ENEL),
- System and component integrity (coordinated by E. Keim, AREVA NP GmbH),
- Fuel, waste and decommissioning (coordinated by S. Napier, NNL),
- Innovative Light Water Reactor (LWR) design, (coordinated by M.-L. Caron-Charles, AREVA NP),

- Harmonization, (coordinated by G. Bruna, IRSN),
- In-service inspection and non-destructive examinations (coordinated by O. Martin, JRC/IET).

The 2nd and 4th technical areas extend beyond the domains that are addressed in this paper:
- The 2nd one includes also the SA impact on the environment in the near-field around the NPP, focusing on atmospheric dispersion of radio-nuclides, and the methods and tools for emergency preparedness and response.
- The 4th one covers more generally the improvement of knowledge and methods in order to increase the safety and availability and control the lifetime of systems, structures and components.

NUGENIA is an open innovation platform with a process of creation of projects based upon members' initiatives that is simple and has proven to be efficient in the NULIFE frame:
- Transparency through a web-based open innovation platform that allows all NUGENIA members to get informed and involved,
- Strategic alignment with technical review by NUGENIA area leaders, orientations, funding advice and labelling by NUGENIA Executive Committee,
- Support specific services/assistance for project preparation, management and dissemination proposed by NUGENIA.

NUGENIA will also help projects by identifying the best available sources of funding. This funding may come from industry or other members, from the European Commission, national resources or even international sources. NUGENIA also offers several other services, such as high-level support for harmonization, and a professional communication and dissemination service.

2.3 NUGENIA R&D roadmap

The R&D roadmap that will address the 8 above technical areas is based on:
- SNETP SRA in its 2009 version,
- Priorities expressed by the following entities: SNETP, NULIFE, SARNET, ENIQ (European Network for Inspection and Qualification), ETSON (European Technical Safety Organisations Network) [3],
- Priorities expressed by public and private end-users,
- National roadmaps (ANCRE in France, SAFIR in Finland…).

Its objectives will be:
- To prioritise R&D challenges for future collaboration within NUGENIA,
- To link R&D challenges to the project portfolio as a basis for joint research (international, European and national programmes),
- To facilitate the emergence of innovative projects,
- To avoid gaps and duplications in the technical coverage, and to ensure the appropriate coupling between technical areas,
- To promote and harmonise European nuclear Gen.II & III collaborative R&D and integrate national research programmes,
- To implement the recommendations of SNETP on the R&D implications of Fukushima and the European stress tests.

The roadmap is currently under elaboration in autumn 2012, with a close and efficient coordination across the 8 technical areas between each leader, the Executive Committee and the Secretariat.

3 FOCUS ON NULIFE R&D PERSPECTIVES ON MATERIALS AGEING

3.1 Context on materials ageing

The specific mechanisms and phenomena that are responsible for the ageing behaviour of materials in LWRs can be assessed by methods and procedures based on representative experimental data. For the example of the reactor pressure vessel (RPV), it can be stated that during the NPP operation the neutron flux affects the RPV material properties. Irradiation of ferritic steels by (fast) neutrons with sufficiently high energy causes interactions of the neutrons with the atoms of the RPV steel influencing the microstructure of the irradiated material. The mechanisms responsible for these irradiation-induced embrittlement effects are well known in terms of matrix damage: Cu precipitation containing Ni, Mn, Si, and grain boundary segregation of P. In order to assess the real ageing behaviour it is useful to investigate RPVs of decommissioned plants.

Thermal ageing refers to hardening caused by thermally activated diffusion of alloying elements or impurities. The potential for thermal ageing embrittlement in LWR RPV steels for times of up to 40 years is considered as low, but cannot be entirely dismissed on the basis of available data.

It is known that hydrogen may contribute to the embrittlement of RPV steels, but only under very specific conditions. The resistance of the steel for hydrogen embrittlement is dependent on the chemical composition, fluence, irradiation temperature and the type of irradiation-induced defects.

3.2 State of the art on metallic materials ageing

Ageing and their effects on material properties have been investigated since the beginning of nuclear power. In-house research and collaborative research programmes led to a considerable knowledge in the understanding of ageing mechanisms and relevant data bases have been created worldwide.

In the 6th and 7th Research Framework Programmes (FP) of the European Commission several research projects have been carried out and have been placed as umbrella projects under NULIFE. Main efforts were put on metallic materials, in the understanding of irradiation effects of RPV materials (examples of EC projects PERFECT, PERFORM-60, LONGLIFE) and in the creation of reliable data bases, but also in other structures like piping (example of EC project STYLE) where one case study addressed the behaviour of an aged austenitic pipe (Figure 4).

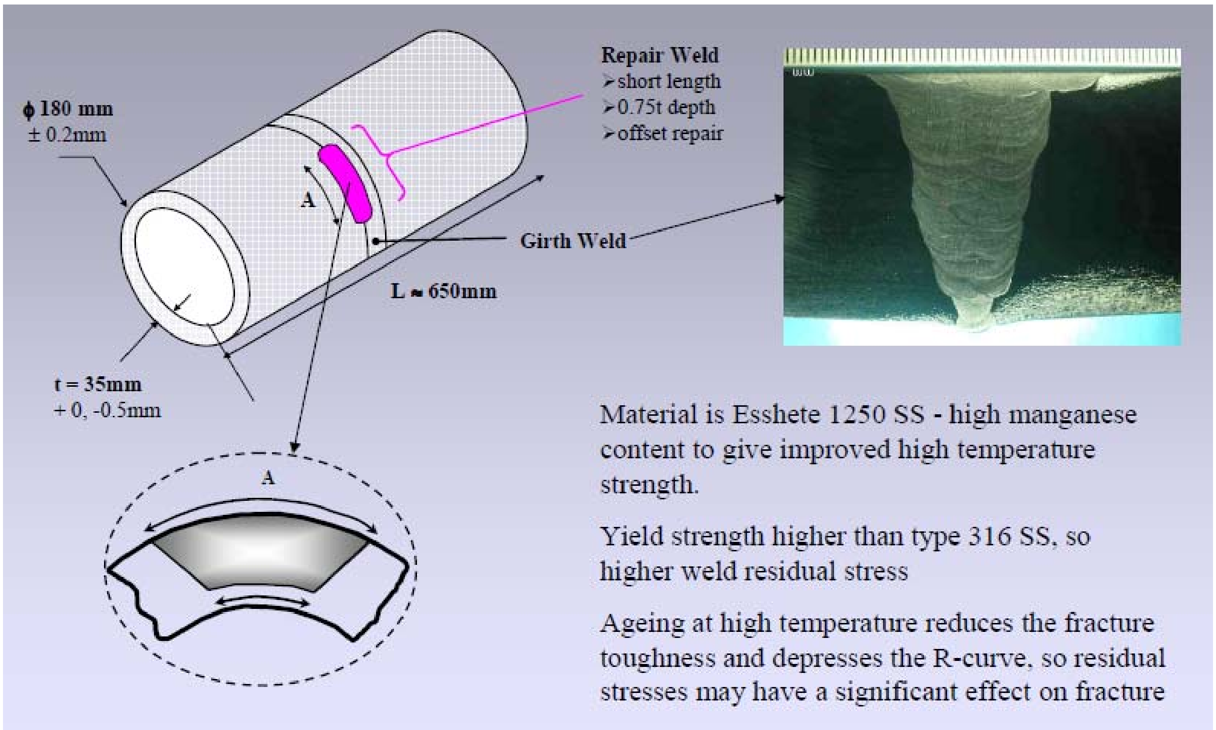

Figure 4: Aged austenitic pipe containing a repaired butt weld in the FP7 project STYLE [4]

3.3 Main R&D priorities issued from NULIFE

The main R&D priorities, based on the outcomes of NULIFE, are summarized in the following domains of materials performance and ageing of mainly metallic materials:

- material properties,
- ageing and degradation mechanisms,
- modelling of ageing.

3.3.1 Material properties

The highest priority R&D concerns: relevant and reliable material properties for extended service and creation of a radiation embrittlement database leading to the development of an improved trend curve for RPV life assessment evaluations. In addition efforts should be put on such aspects as the treatment of scatter, corrosion and environmental-fatigue data to be applied correctly in integrity assessments. Another complex issue should be addressed too: how manufacturing processes (including welding, thermal and mechanical treatments and coatings) may affect materials and material properties and how such processes may be improved in the future.

3.3.2 Ageing and degradation mechanisms

The highest priority R&D is to get a better knowledge of ageing mechanisms. The goal is to anticipate and acknowledge ageing issues that may evolve during the foreseen extended life. The identified technical subjects are corrosion fatigue, irradiation embrittlement, stainless steel cracking and concrete ageing. In case of very long times, possibly exceeding 60 years of operation, several ageing mechanisms that previously have been deemed of lesser importance, such as creep and thermal ageing, may become life limiting factors that need to be addressed.

3.3.3 Modelling of ageing

A good start has been made on developing multi-scale based models for some ageing and degradation mechanisms. In particular the modelling of irradiation embrittlement in RPV steels is a good example (see Figure 5). However, on this aspect, as well as on other ageing and degradation mechanisms, significant work is still required for the long term.

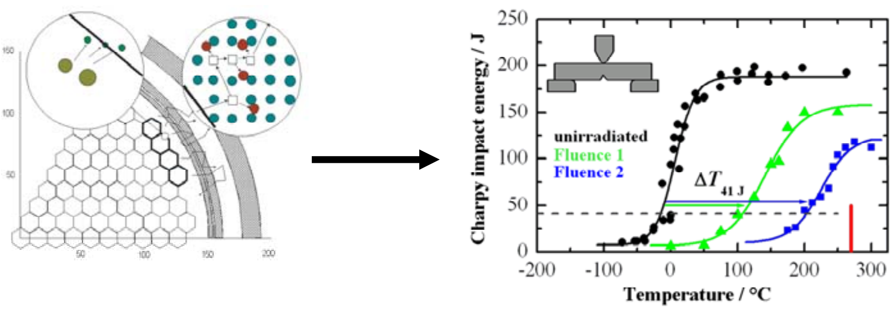

Figure 5: Prediction and surveillance of RPV neutron irradiation embrittlement (FP7 project LONGLIFE) [5]

The highest priority R&D concerns the improvements for a better physical understanding of all relevant ageing mechanisms and their driving parameters. The objective is to identify not only the thresholds for defect initiation and the kinetics for defect propagation, but also the precursor state that leads to defect nucleation. There is a need to be able to make reliable long-term predictions of ageing and its effects. This entails being able to model fundamental phenomena in physics and chemistry at different scales from atomic to macroscopic. Model parameters must be validated against data from laboratory experiments or, most importantly, from operating experience feedback.

4 FOCUS ON SARNET R&D PERSPECTIVES ON SEVERE ACCIDENTS

4.1 Context on severe accidents

Despite the highly efficient accident prevention measures adopted for the current Gen.II and the still more demanding ones for the Gen.III plants, some accident scenarios may, with a low probability, result in SA, as recently emphasized with the Fukushima-Daiichi accidents in Japan. This SA can eventually end-out in core melting, plant damage and dispersal of radioactive materials out of the plant containment, thus threatening the public health and the environment. It is now particularly important to evaluate and improve the Severe Accident Management Guidelines (SAMGs) and to design new prevention devices or systems for mitigation of SA consequences.

Forty-seven partners from Europe, Canada, India, South Korea, United States and Japan participate in the SARNET (Severe Accident Research NETwork) consortium with an overall man-power that represents about 40 persons per year (230 researchers and more than 20 PhD students are involved in the network). This network of excellence has been launched in 2004 in the frame of the EC FP6 in order to optimize the use of the available research budget and to constitute a sustainable consortium in which common research programmes in severe accident (SA) area and a common SA computer code (ASTEC) are developed. A 2nd project [6] has been defined in continuity in the FP7 frame in order to reach the self-sustainability after its end in March 2013. Both FP projects have been coordinated by IRSN.

4.2 State of the art on severe accidents

An essential brick of the network was, since its start in 2004, the establishment of a ranking of R&D priorities, using a well-founded and trackable process. To be sure that the research conducted on severe accidents is efficient and focusing on relevant topics, a group of SA specialists, coming from various types of partners (industry, vendors, R&D, TSO), was created and led by GRS: SARP or Severe Accident Research Priority. The approach was based on the PIRT one adopted in the EURSAFE FP5 project [7], on the basis of two evaluations, the safety importance ratio and the knowledge ratio.

At the end of the FP6 project, the SARP group ranked the main SA research priorities [8] that were used to define the structure of the next FP7 project, i.e. the Work-Packages and their content, i.e. the main R&D tasks to be performed. Six among the 21 issues were considered with high priority (see § 4.3), four issues were re-assessed with medium priority and five with low priority. Again, in 2011-12, these conclusions have been updated by taking into account:

- the progress of international R&D, with most recent experimental results from mainly: SARNET, R&D projects in the OECD/NEA/CSNI Group on Analysis and Management of Accidents (GAMA), International Source Term Programme (ISTP) International Science and Technology Centre (ISTC) projects,
- the remaining safety issues as highlighted by Level 2 PSA studies as being of high priority for reducing uncertainties, e.g. in close link with the ASAMPSA2 recent FP7 project [9],
- and the preliminary lessons learnt from the Fukushima accidents.

The SARNET synthesis reports that will be published in the 2nd part of 2013 will summarize the progress done after 4 years in the SA domain.

4.3 Main R&D priorities issued from SARNET

The recent SARP update [10] has kept the high priority for the 6 same following issues, although significant progress has been made on knowledge (even allowing the near closure of sub-issues) :

- Core coolability during reflooding and debris cooling,
- Ex-vessel melt pool configuration during Molten-Core-Concrete Interaction (MCCI) & ex-vessel corium coolability by top flooding,
- Melt relocation into water & ex-vessel Fuel-Coolant-Interaction (FCI),
- Hydrogen mixing and combustion in containment (flame acceleration),
- Oxidising impact on source term (Ruthenium oxidising conditions, air ingress for high burn-up and MOX fuel elements),
- Iodine chemistry in circuits and in containment.

A few changes occurred mainly in relation with Fukushima: some SA topics get higher relevance, such as melt and debris coolability, hydrogen explosion or containment venting and filtering, and a few new issues (R&D was existing but with a low intensity) need to be addressed such as pool scrubbing under boiling conditions, behaviour of spent fuel pools, and ad-hoc instrumentation for SA diagnosis. It must be underlined that most physical phenomena that occurred in Fukushima were already considered in SARNET as high-priority subjects.

4.3.1 Core coolability during reflooding and debris cooling

The main current uncertainties concern the efficiency of cooling the reactor degraded core, with presence of corium and/or solid debris, by water addition to limit or terminate the SA in-vessel progression. A map for degraded core reflooding was built by KIT by including updated experimental data and theoretical work: this “living” map will be used to identify areas for efficient future experimental work.

Significant efforts are currently done in SARNET on the subject of debris bed formation and coolability. Several experimental programmes, with complementary characteristics, are under way in different organizations, some of them addressing specifically ex-vessel situations:

- DEBRIS (Univ. Stuttgart), PRELUDE and PEARL (IRSN), COOLOCE (VTT) on debris coolability,
- DEFOR and POMECO (Univ. of Stockholm) on melt jet fragmentation, debris formation and coolability, particle debris spreading, particularly for ex-vessel situations,
- QUENCH-Debris (KIT) on debris formation from a bundle,

Figure 6 shows the PEARL facility, near the end of construction in IRSN, which addresses reflooding of debris beds in 2D geometry. The most recent results of some abovementioned experiments, e.g. those of the PRELUDE smaller-scale facility, have underlined an increased coolability in 2D geometry compared to earlier understanding and to past 1D experiments.

Modelling work is also ongoing, first in mechanistic codes such as MC3D and ICARE/CATHARE (IRSN), DEM and DECOSIM (KTH) and ATHLET-CD/VECO (Univ. Stuttgart, GRS), and secondly in the ASTEC integral IRSN-GRS code (see § 4.3.6).

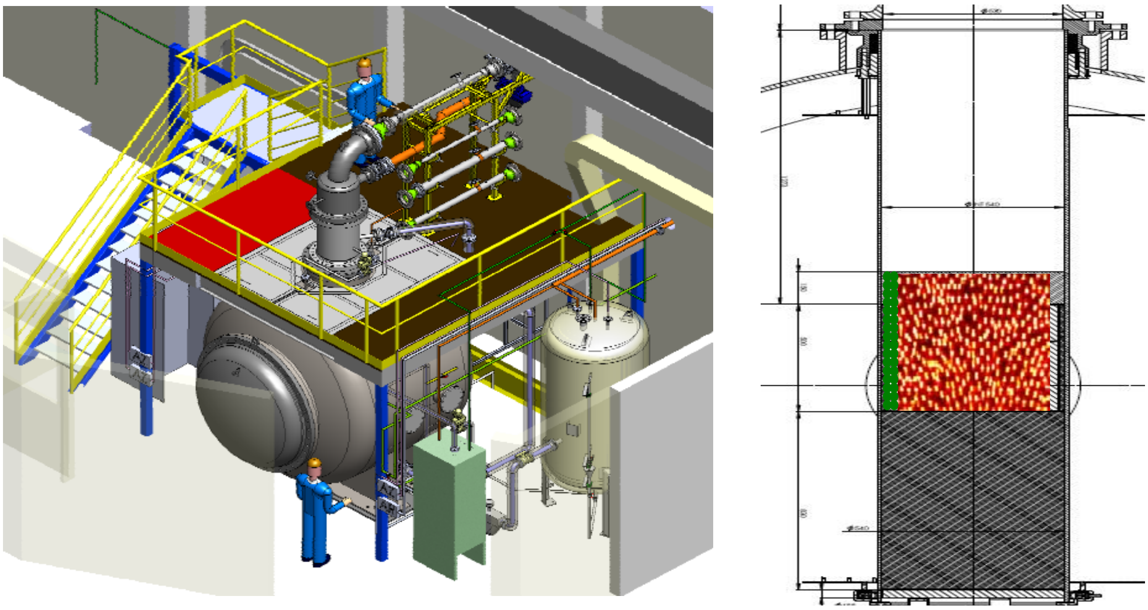

Figure 6: PEARL IRSN facility for debris bed reflooding

Another high priority R&D issue is in-vessel melt retention, which implies a better knowledge of firstly corium pool coolability within the reactor pressure vessel (RPV) lower head, especially for BWRs with presence of control rod and instrumentation guide tubes, and secondly on RPV external cooling conditions.

4.3.2 Ex-vessel MCCI & corium coolability by top flooding

If the RPV lower head fails, corium will be transferred to the cavity where MCCI will take place, either in dry conditions or with top flooding by water resources available in containment. It is important to preserve the containment integrity against slow basemat melt-through.

Several 2D MCCI experiments in prototypical corium materials (VULCANO, HECLA…) and analytical experiments in simulant materials (MOCKA, CLARA…) are performed or analysed in SARNET. Progress has been done to explain the origin of anisotropic ablation for silica-rich concrete and isotropic one for limestone-rich one but R&D must continue. The MCCI codes benchmarks in reactor geometry have indicated a large scattering in axial ablation results in the case of stratified corium pool configurations. Large uncertainties remain on oxide-metal corium interactions.

4.3.3 Melt relocation into water & ex-vessel FCI

A major safety challenge is to preserve containment integrity against rapid failure by steam explosion. The work is being done in complement to the OECD SERENA2 project. A better understanding of phenomena (like pre-fragmentation, effects of void and sub-cooling) has been obtained but however the issue is still far from resolution.

4.3.4 Containment behaviour

The safety challenge is to preserve containment integrity against failure by over-pressurisation due in particular to combustion and possible explosion of gases that accumulate in containment (hydrogen from core oxidation and carbon monoxide from MCCI).
New experimental data have been made available on formation of combustible gas mixtures, local gas composition and potential combustion modes (ENACCEF exp.), and on reaction kinetics inside catalytic recombiners (REKO-3 exp.).
But R&D should continue on containment atmosphere mixing and gas combustion, in particular accounting for the influence of mitigation systems. Scaling (qualitative and quantitative) of phenomena from experimental facilities to actual containments should also be addressed with priority.

4.3.5 Source term

The safety challenge is the reduction of source term by proper measures for limitation of uncontrolled leaks of the containment and for improvement of filtering efficiency of containment venting systems.

Three main issues are addressed with many ongoing experiments (EXSI in VTT, VERDON in CEA, RUSET in AEKI, CHIP and EPICUR in IRSN, etc…) and modelling efforts (in priority in ASTEC):

- Oxidizing environment impact on FP release from fuel, in particular for ruthenium, i.e. under oxidation conditions or air ingress for high burn-up and MOX fuels;
- High temperature chemistry impact on FP behaviour in the RCS, i.e. improving predictability of iodine species exiting RCS towards the containment Iodine and ruthenium transport in RCS;
- Iodine chemistry in containment.

R&D must continue on the three above issues. The Fukushima accident underlined the need of studying the impact on source term of the containment filtered venting and of pool scrubbing, which are important radionuclide removal processes.

4.3.6 Severe accident simulation codes

Important efforts have been done in SARNET on the assessment and the improvement of the ASTEC integral code (see Figure 7), jointly developed by IRSN and GRS [11] [12]. Such type of code (also called system of codes) allows to simulate the SA complete scenarios up to the evaluation of the source term into the environment, as well as to evaluate SAM measures. Most of the knowledge acquired in SARNET is being capitalized in ASTEC through new models or improved models. There is a clear need for improvement of BWR-specific models accounting for Fukushima accident analysis and for validation against existing experimental data and future experiments. The ASTEC adaptation to BWR core degradation is ongoing in 2011 and the feedback of the interpretation of the Fukushima accidents in the coming years will be used to validate these new models.

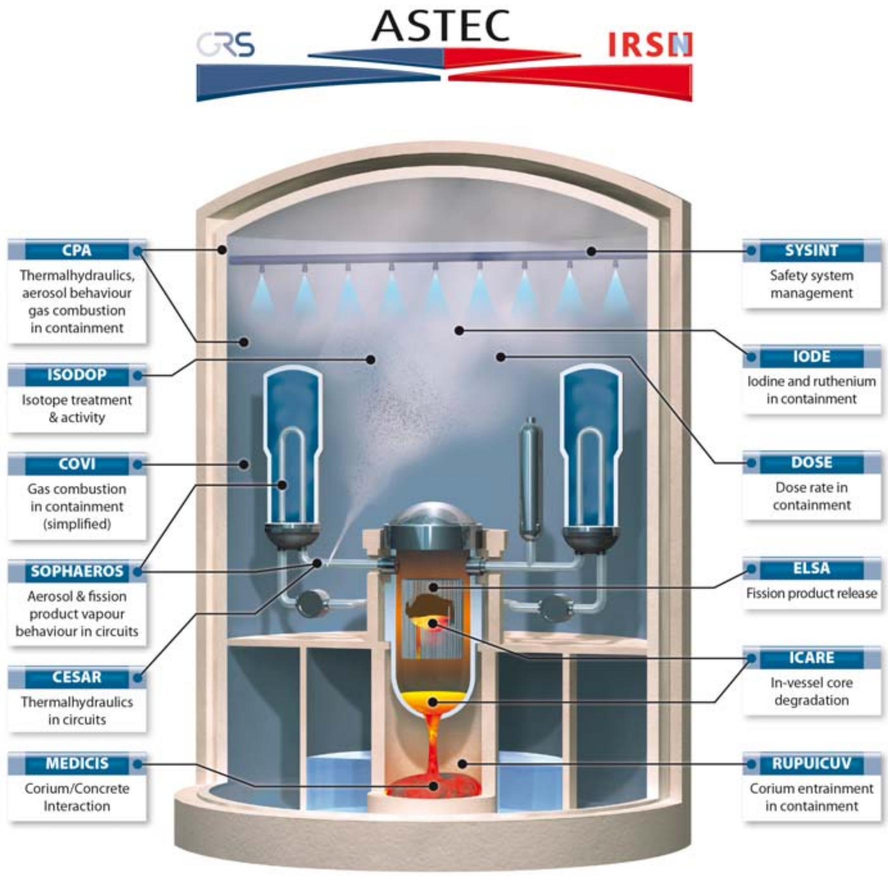

Figure 7: ASTEC integral code for simulation of severe accidents

5 CONCLUSIONS AND PERSPECTIVES

End of 2012, NUGENIA is ready to work with statutes, internal rules defining its governance, portfolio of current R&D projects (mainly based, for the moment, on projects launched under the NULIFE auspices), and eight technical areas. The current efforts focus on the elaboration of a Strategic Research Agenda for short, mid and long term. It will be finalized in early 2013 and a chapter derived from the roadmap summary will be integrated in the SNETP SRA update that is planned in 2013.

Discussion will take place to widen the NUGENIA membership, first to all EU Member States, and then to countries out of Europe. In the next months, the legal links with SARNET have to be formalized, with a partial or total integration of the network and taking into account the need to continue the fruitful collaboration on severe accidents with non-European partners.

The next step is to set up a strong and coordinated portfolio of collaborative R&D projects. For example in the SA domain, two new FP7 projects are going to start in early 2013: PASSAM (coordinated by IRSN) on passive and active systems for SA mitigation, and CESAM (coordinated by GRS) on ASTEC improvements for SAM and account for Fukushima lessons.

NUGENIA is currently preparing a proposal, named NUGENIA+, to answer the EC call, published in July 2012, on the Topic Fission-2013-2.1.1 “Preparatory Phase (PP) in support to an efficient EU integrated research programme on safety of existing nuclear installations”. This proposal aims at showing the NUGENIA capability to manage internal calls for new R&D projects, both on a technical and financial point of view. It should allow reaching an optimal coordination between NUGENIA R&D programmes and the national programmes of Member States, with co-programming based on public-private partnerships at the European level, and with a longer term objective of deeper integration of programmes.

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