November 2011

EUROSAFE TRIBUNE

Towards Convergence of Technical Nuclear Safety Practices in Europe

20

Prevent **severe accidents and** prepare **for emergency management**

What research in Post-Fukushima times?

ETSON views within SNETP

SPECIAL FOCUS: FUKUSHIMA-DAIICHI LESSONS

page 31

Establishing priorities for safety research

A major aim of future nuclear safety research is not only to deepen knowledge of the physical and chemical phenomena at work in nuclear facilities, but also to study the potential impact of external and internal loads considered up to now as not expectable.

To our readers

The ability of European TSOs to analyse in real time the Fukushima-Daiichi NPP accident and to keep the public informed of its potential consequences draws upon two main resources: properly staffed and trained technicalcrisis centres on the one hand, and the real-time usage of up-to-date scientific knowledge on severe accident phenomena on the other hand. This knowledge is the result of a long-term process which encompasses state-of-the-art theoretical developments pertaining to the transient behaviour of fluids, structures and nuclear fuels, as well as to aerodynamic aerosols dispersion and the assessment of the subsequent radiological impact on the population. To achieve such short-time response capability, no less than three decades of safety research were necessary, bearing witness to the science-based nature of safety expertise.

This inescapable reality is acknowledged by the 97 European Sustainable Nuclear Energy Technology Platform (SNETP) member organisations, just as is the belief that the future of nuclear energy in Europe and the rank of the EU in nuclear technology in the international competition will depend, first and foremost, on the safety performance of its nuclear power plants. ETSON, the European TSO Network, shares these views and is committed to continuously contribute to the enhancement of safety in nuclear facilities.

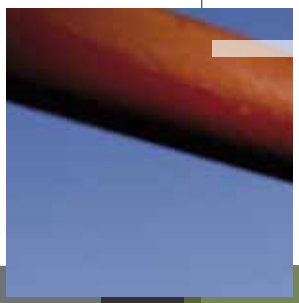
ETSON member TSOs also share the view that the enhancement of safety still requires much theoretical and experimental research work to be carried out, notably to take into account extreme or combined external and internal hazards, which were assumed to be so unlikely that they were not fully taken into account. Substantial progress has been achieved in the past decades to gain knowledge of the physical and chemical phenomena at work in nuclear plants, as well as of the way plants are operated. This was undoubtedly conducive to safety improvements. Nevertheless, a lot can still be done to better prevent severe accidents and mitigate their consequences.

This is why several ETSON member TSOs joined SNETP and, as a contribution, drafted a position paper aimed at presenting their views on the safety issues associated with the different generations of nuclear plants and the definition of relevant priorities for future research programmes.

Through a series of articles – debates, interviews, etc. – the present issue of the EUROSAFE Tribune is intended to highlight and to comment on the main topics dealt with in this position paper.

What research for what safety enhancement? We are pleased to invite you to making your own judgement on this subject and we wish you pleasant reading.

Jacques Repussard and Frank-Peter Weiß



Safety research **06**

Promoting European excellence in nuclear technology is first and foremost a matter of safety research.

Human factors **19**

Preventing situations potentially conducive to accidents and enhancing preparedness to emergency situations.

The EUROSAFE Tribune 20

The EUROSAFE Tribune is a periodical from the EUROSAFE Forum *published jointly by GRS and IRSN as a contribution to the EUROSAFE approach.*

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Printing
Media Cologne, Hürth

ISSN: 1634-7676
Legal deposit: November 2011

The EUROSAFE Tribune is available on the website: www.eurosafe-forum.org

Printed using vegetable inks and totally chlorine free, 100% recyclable and biodegradable, semi-matte coated paper.

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The enhancement of nuclear safety and radiological protection still requires much theoretical and experimental research work to be performed.

- *We'll need to reassess all the levels of defence-in-depth as well as the physics of the associated events to push back the limits in terms of probability and consequences of an accident.*

Lars Skånberg, SSM page 20

Fukushima-Daiichi lessons **31**

Considering potential risks, as unlikely as they might appear, and developing the necessary competences accordingly.

November 2011

Cover picture:
Unloading operations of Cabri research reactor core.

Kaleidoscope

MEETINGS

29 November 2011
SNETP 3rd General Assembly, in Warsaw (Poland).
More information on:
http://www.setplan2011.pl/

5-8 December 2011
Seminar devoted to Innovative Nuclear Power in Closed Fuel Cycle Scenario.
At the Physikzentrum Bad Honnef (Germany).
More information on:
http://www.nuklear.kit.edu/75.php

21-23 March 2012

5th European Review Meeting on Severe Accident Research (ERMSAR) conference hosted by GRS in Cologne (Germany).
More information on:
www.sar-net.eu/

ETSON NEWS

Two new associate members:
The State Scientific and Technical Centre of Nuclear and Radiation Safety (SSTC) of Ukraine and the Japan Nuclear Energy Safety Organization (JNES) joined ETSON as associate members on Nov. 8th, 2010.

KEY INDICATORS

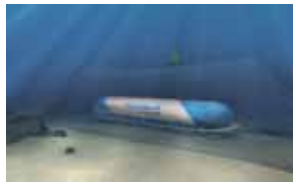
According to the IAEA:

441 commercial nuclear power reactors were in operation worldwide in 2010 with a total net installed capacity of 374.633 GWe.

60 commercial nuclear power reactors were under construction worldwide in 2010 with a total net electrical capacity of 58.6 GWe.

NEW CONCEPTS

Flexblue



A small nuclear power plant producing 50 to 250 MWe to be installed on the seafloor off the coast of maritime nations. Designed jointly by AREVA, CEA, DCNS and EDF.

STRATEGY

SNETP strategic documents downloadable at www.snetp.eu > Publications > Strategic documents

- Vision Report
- Strategic Research Agenda
- Deployment Strategy
- EKTM report
- European Sustainable Nuclear Industrial Initiative (ESNII) brochure

WWW

SNETP Newsletter: release of the 8th issue featuring a special focus on SNETP's reaction to the Fukushima-Daiichi nuclear accident. Downloadable at www.snetp.eu > Publications > Newletters > Newsletter no. 8

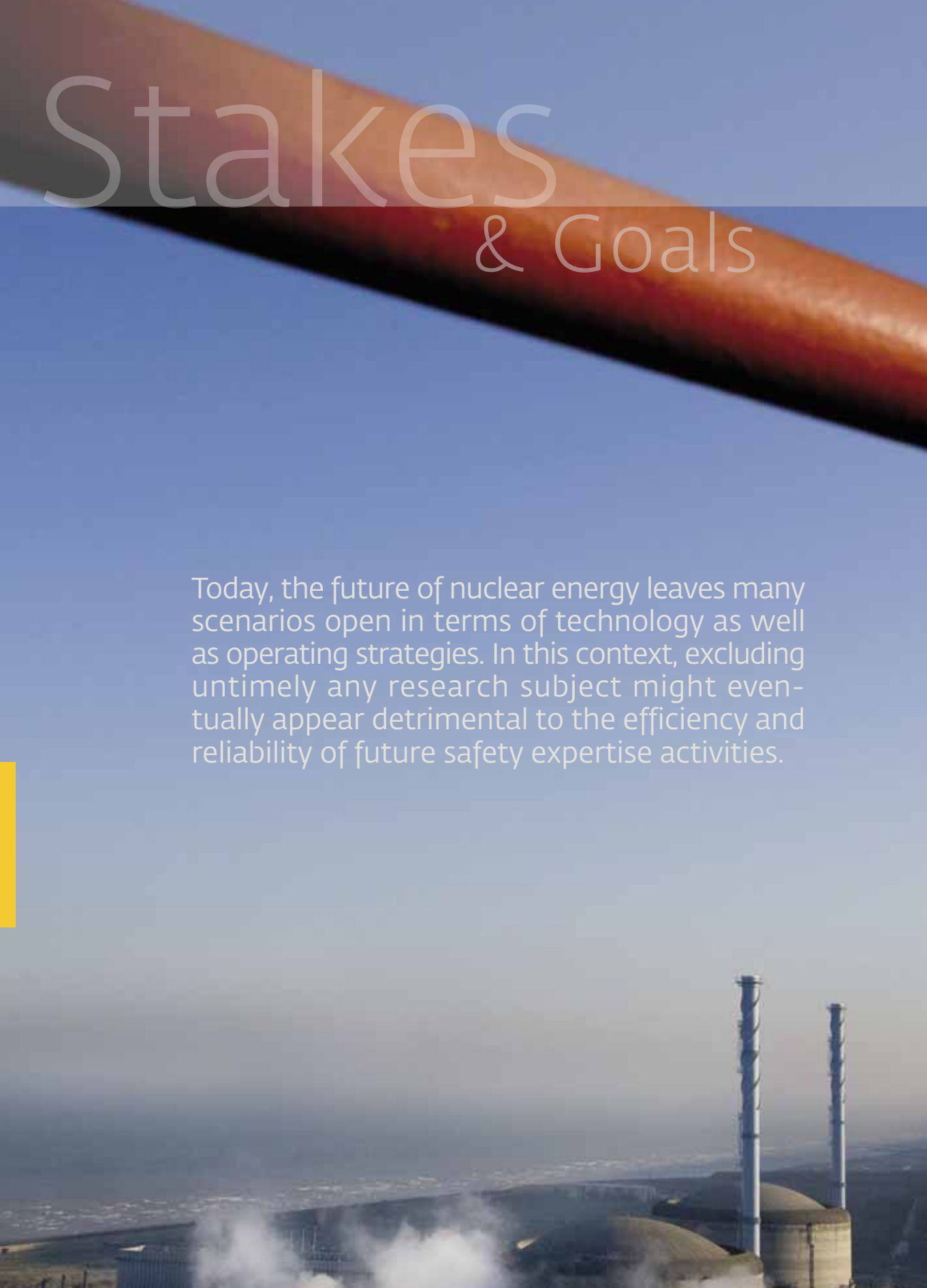
Nuclear Education and Training: Key Elements of Sustainable European Strategy, study released by the SNETP Working Group on Education, Training and Knowledge Management (ETKM). Downloadable at www.snetp.eu > Education, Training and Knowledge Management

NULIFE Bulletin: release of the 3rd issue featuring the future NULIFE Association as well as NULIFE umbrella projects LONG-LIFE and STYLE. Downloadable at www.vtt.fi/proj/nulife > Publications > NULIFE Bulletin Number 3

Severe Accident Research Network of Excellence Newsletter n°4: featuring notably the impact of the Fukushima-Daiichi accident on SARNET. Downloadable at www.sar-net.eu/node/81

Stakes & Goals

Today, the future of nuclear energy leaves many scenarios open in terms of technology as well as operating strategies. In this context, excluding untimely any research subject might eventually appear detrimental to the efficiency and reliability of future safety expertise activities.



Nuclear safety research: leave the doors wide open

On a human timescale, nuclear energy is definitely a long-term commitment. Over a hundred years or more, unexpected events can occur and influence the foreseeable course of events, starting with natural hazards, such as the Great Tohoku earthquake and tsunami that stroke the Fukushima-Daiichi nuclear power station on March 11th, 2011. Therefore, dealing with nuclear safety in an appropriate way requires both continuity as well as an open attitude towards change. Since the beginning of the 60s, safety research has become progressively more important in order to understand the phenomena and sequences conducive to core meltdown. Today, experts still need to take efforts to improve the calculation beyond the first 220 minutes of the Three Mile Island-2 (TMI2) accident, and the work on environmental and human consequences of accidents still requires further development ◆ ◆ ◆

◆ ◆ ◆ Even if nuclear energy remains a long-term commitment, the nuclear map keeps changing at a sustained pace, with new countries accessing nuclear power and new products being launched, more and more as a result of international co-operation projects, such as the APR 1400 (Korea-US) or ATMEA (France-Japan) reactors. Increasingly international products call for a worldwide alignment of safety assessment approaches, calling in turn for cross-border partnerships among the stakeholders involved in the safety of nuclear facilities. In this context, the EUROSAFE and **> ETSON <** organisations and the Sustainable Nuclear Energy Technology Platform (SNETP) aim at promoting unprecedentedly high safety and quality levels, thereby providing Europe with a major competitive advantage at a time where the public shows itself to be particularly concerned by nuclear safety issues across the globe.

> Definition <

A definition of all the terms highlighted this way is given in the Glossary on p. 36.

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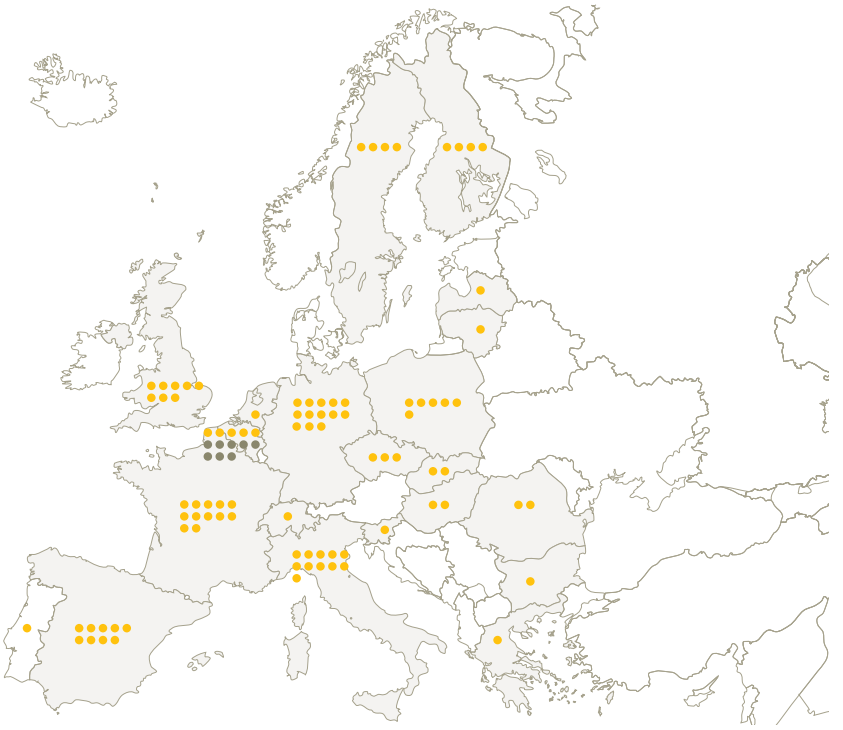
European stakeholders from the industry, research, academia, technical safety organisations, non-governmental organisations and national representatives are brought together within SNETP.

Promoting European excellence in nuclear technology, a matter of safety research

Since the beginning of the EUROSAFE approach, the safety organisations have shared more efficiently the build-up of the competences with the aim to delivering safety evaluation at a constant up-to-date level. In the past, many exercises have been realised against the European Framework Programme (EC FP) background in order to identify the subjects to put in light and in priority: for instance, the EURSAFE concerted action exercise at



the end of 90s was realised as a PIRT (Priority Identification and Ranking Table) devoted to safety of the NPPs; this resulted the in launching of the SARNET project. Many similar exercises are performed at national level or against the background of the NEA.
Since 2007, the Sustainable Nuclear Energy Technology Platform (SNETP) has been gathering all the European stakeholders in the nuclear field in order to promote research, development and demonstration of the nuclear fission technologies necessary to achieve the **SET-Plan** goals in this field. Among the main objectives to be achieved by the year 2020, the Plan aims at maintaining competitiveness in fission technology. Today, considering that safety is one of the main indicators of competitiveness, the European Technical Safety Organisations Network (ETSON) is very active in the working groups and in the governing structures of this technology platform and was encouraged to express views on safety priorities. As a group of TSOs within SNETP, they issued a position paper meant to be a living document conveying their views on research priorities for the safety of GEN II and GEN III NPPs. This paper will be presented to the European Commission and to other international organisations.

SET-Plan

In order to combat climate change, the EU has committed for the year 2020 to reduce by 20% its greenhouse gas emissions compared to 1990, make 20% energy savings and include a 20% share of renewable energies in the total energy mix. To reach these goals, the Strategic Energy Technology Plan (SET-Plan) identifies a set of competitive low-carbon energy technologies to be developed and deployed in Europe, with nuclear fission representing a key contribution.

www.snetp.eu/

An expectable reshuffling of nuclear safety research projects

Many nuclear power research projects are currently in progress, either as part of the EC FP or through international organisations, or directly through co-operation at international or national levels. Some of them contribute through their results to developing expertise in nuclear reactor safety. A major characteristic feature of the TSOs is the duty of a constant questioning aimed at enhancing nuclear safety and the duty to maintain the subsequent capability. *"Today, this questioning applies evidently to the*

The provisional subjects proposed by JNES to its national authorities can be summarised as follows:

- Investigation, analysis and evaluation of the Fukushima-Daiichi NPP accident and of its environmental impact.
- Evaluation of the seismic source model, ground motion and tsunami taken into consideration for the Tohoku region regarding Pacific Ocean earthquakes.
- Research on the evaluation of effectiveness of conventional seismic and tsunami countermeasures taken for nuclear reactor facilities.
- Durability evaluation of nuclear equipment exposed to seawater.
- Study of (radioactive) waste disposal around the NPP site in the wake of the disaster.
- Enhancement of fuel cycle facilities safety.

Fukushima-Daiichi Nuclear Power Plant (NPP) accident (see Special Focus on p. 31) *and will influence not only the basic philosophy of nuclear safety expertise but also the priorities of the already planned safety research, putting in light new research needs, as evidenced in the chapter of the TSOs' position paper devoted to priorities in R&D for nuclear safety"* emphasises Andreas Pautz, Head of Reactor Safety Research Division at GRS.

This accident will go on influencing the medium- and long-term research, as more in-depth analysis becomes available, notably as a result of the set of provisional subjects proposed by JNES, the Japanese TSO, to its national authorities (see opposite box). Safety organisations are working on these issues and will develop their own views and corresponding research orientations, e.g. through the EUROSAFE working group and other international organisations. *"The TSOs' role within SNETP must be acknowledged, just like the role of the other partners, and no R&D subject should be excluded, as it may come on the agenda sooner or later, upon examination of the safety cases,"* stresses Edouard Scott de Martinville, an IRSN representative among the platform, in a clear plea to leave the doors of nuclear safety research wide open.

No R&D subject should be excluded, as it may come on the agenda sooner or later, upon examination of the safety cases.

The TSOs' key role within SNETP

Whereas designers and operators are primarily interested in the development of energy systems with due involvement in safety demonstration, the safety organisations are committed above all to assessing the safety features of these systems. As a consequence, research supporting safety assessment is devoted to understanding any phenomenon that would jeopardise the safe and secure implementation of nuclear energy systems and to developing reliable and accurate computing tools to represent them. Another aim of research performed by the technical safety organisations is to investigate the methodologies and phenomena that might influence the validity of safety demonstration submitted by the designers and operators ◆ ◆ ◆

◆ ◆ ◆ TSOs therefore have to maintain state-of-the-art knowledge and facilities for safety assessment and to provide, beyond the aggregation of specialised expert findings, a comprehensive and holistic view of the safety issues. Three experts involved in the Sustainable Nuclear Energy Technology Platform (SNETP) — Valéry Prunier (EDF), Marc Deffrennes (EC) and Francisco Fernández-Moreno (CSN) — debate on the role and objectives of TSOs within the Platform in establishing safety research priorities for Gen II and III nuclear facilities, seeking for co-ordination and harmonisation at European level.

Valéry Prunier — I think the first point to be made clear pertains to the need for a unified and unique research frame in nuclear technology that brings together all significant European players from the industry, research centres and universities, as well as the TSOs. Obviously, the goal of the SNETP platform is to give research maximum efficiency. This means to avoid redundancies in R&D organisation and projects, but also to build an even more solid scientific and technical basis, to be shared rationally and used consistently to a promote sustainable use of nuclear energy in Europe, needed to comply with overall economic and environmental requirements. On their side, TSOs will carry out specific research projects aimed at assessing the safety cases submitted by the industry. However, "maximum efficiency" implies not only resources but also methodologies and solutions to be shared, thereby creating consensus in an increased number of areas in a very natural way.

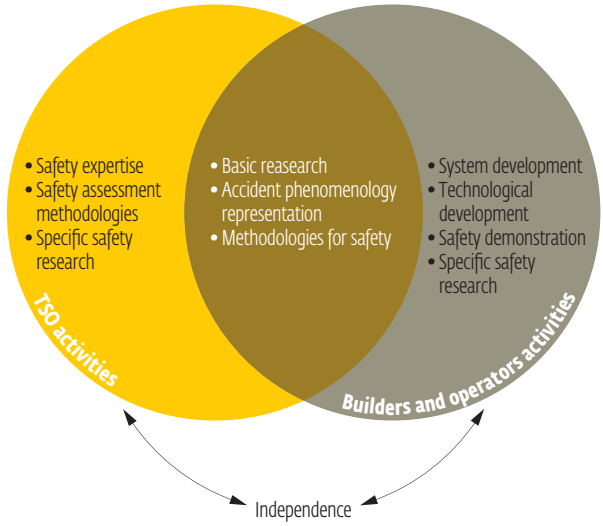
Francisco Fernández-Moreno — Let me reflect from a technical safety organisation's perspective! How will TSOs benefit from this common technology programme called SNETP?

Marc Deffrennes
Head of Sector
DG ENER D2 (Euratom),
European Commission

Francisco Fernández-Moreno
Counsellor
Consejo de Seguridad Nuclear (Spain)

Valéry Prunier
R&D Programmes, Generation
EDF (France)
Chair of NULIFE End User Group,
Chair of SNETP TWG Gen II&III

I think the major advantage from research projects carried out jointly with the industry is a better understanding of the operators' rationale, thus translating into increasingly safety-effective discussions. The joint projects will allow identifying clearly the areas where designers and TSOs already have a common comprehension of issues and those where knowledge is still insufficient to build up this common comprehension. The larger the "common comprehension" areas, the faster the progress achievable through focused research! If you take the > **PHEBUS PF** < as an example, the knowledge gained jointly by all participants on the behaviour of fission products through this programme allowed for instance assessing the source-term at Fukushima-Daiichi after the March 11th earthquake and subsequent tsunami. But uncertainties remain concerning the chemical form of iodine released from the damaged reactors, calling for more focused research programmes such as > **CHIP** < to be performed.



R&D activities of TSOs and utilities
The diagram shows that common research between TSOs and utilities belongs to "safety-oriented" research, i.e. accident phenomenology and assessment methodology. Such research allows cost optimisation through shared investments in common programmes while securing each stakeholder's independence through the possibility to perform in parallel one's own safety research.

Marc Deffrennes — As a representative of the European Commission which supports the SNETP platform, I fully agree with you, Francisco, on the importance of having the European TSOs (grouped in ETSON) actively involved in the Platform, among other stakeholders, recognising the specific role they are playing. Nuclear energy provides 2/3 of the low-carbon electricity in the EU today and we all know the ambitious carbon reduction targets and objectives the EU has defined for itself for 2020/2050. At the same time, we are aware of the concerns related to security of energy supply and overall competitiveness, and so I believe that nuclear energy will continue to be an important contributor to the energy mix in the future. For this to happen, safety must stay the first priority, and even more today after the events in Japan. This safety aspect is already well integrated into SNETP where research priorities are defined after extensive discussions among the members in their specific roles: technology suppliers, operators, TSOs, research organisations. This is why such a platform is in a position to showcase European excellence in this field.

Francisco Fernández-Moreno — Excellence is first and foremost a matter of competence of the staff tasked with nuclear safety, and competence has to be required and main-

tained from the recruitment of new staff members, based on demanding enrolment criteria, through to the ongoing improvement of knowledge through participation in research. This shows how useful European education & training initiatives are, notably those triggered by TSOs, as a means to enhance the competence of safety engineers based on an exchange of views on methods, experience and research.

Valéry Prunier — Toward excellence, we have to think and act more at the European level. Today, more than yesterday and less than tomorrow, co-ordination is essential to maintain and develop top level expertise and facilities as needed in all aspects of nuclear technology. The SNETP philosophy fits perfectly to obtain more results with limited resources. Its success would be magnified if some public decision-makers, following all the other members, were to join these optimisation efforts by bringing national nuclear R&D programmes for sharing.

Marc Deffrennes — Improving the level of scientific knowledge is obviously a *sine qua non* condition to maintain a strong European nuclear technology leadership, which is critical at a time we see a number of "newcomer countries" looking at nuclear energy as a low-carbon option for their future energy mix. And, again, safety must be at the core of the knowledge, covering the full scope of risks understanding, assessment and management methods.

Research performed by the TSOs aims at investigating the methodologies and phenomena that might influence the validity of safety demonstration submitted by the designers and operators.

Valéry Prunier — I fully agree, safety first. I would like here to highlight a unique benefit of SNETP: research priorities are implemented while taking into account

the different views of all types of members. For instance, utilities bring the lessons learned from operating experience. This outlines the critical role of TSOs within SNETP in the field of safety and that of the SARNET network regarding the prevention of severe accidents.

Francisco Fernández-Moreno — Well, no need to say that we must do our best to prevent severe accidents. However, I think we should go beyond mere prevention and make progress in mitigating the consequences of accidents. As clearly illustrated by the Fukushima-Daiichi accident, particular phenomena or events that were considered as excluded or eliminated have nevertheless to be studied and their consequences mitigated.

Valéry Prunier — This is one of the reasons why we have recently decided to revise jointly our strategic research agenda for Gen II & III and to detail roadmaps for our seven major technical areas. Contributions from the SNETP TWG on Gen II & III will be combined with those emanating from NULIFE, SARNET and, last but not least, with the expression of research needs given in the TSOs position paper. Implementation through R&D projects will continue and develop in parallel, according to industrial milestones and the member plus external supports to each project.

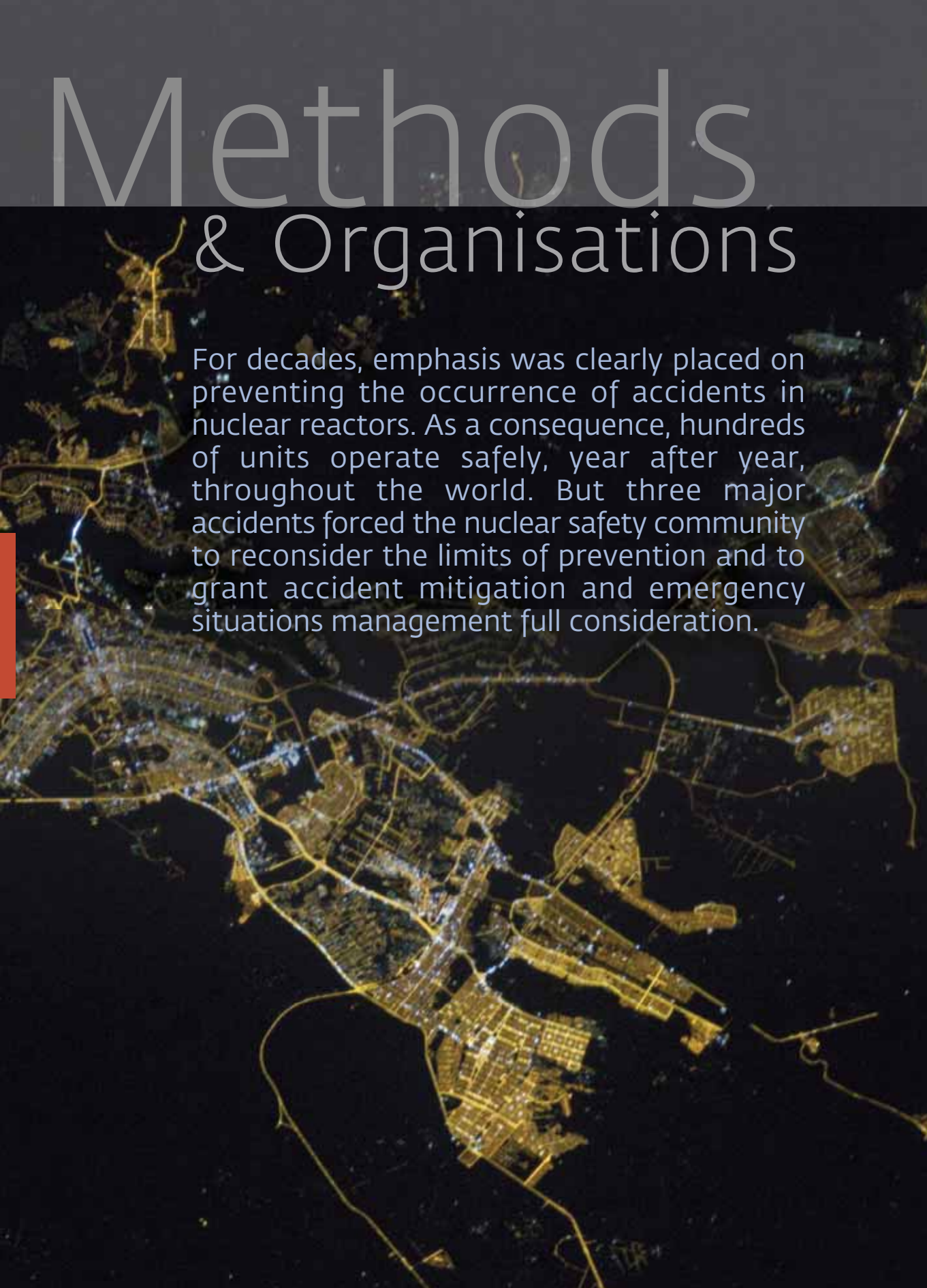
Francisco Fernández-Moreno — I see two other major selection criteria, the first one taking into consideration the safety relevance of the barriers existing in the design of the nuclear power plants, the different threads and the possibility of breach of the three barriers, and the associated safety margins. The second, very practical, criterion is the degree of importance and urgency of a research programme regarding the challenges faced by the regulatory bodies, and keeping in mind that the TSOs support regulatory bodies with technical and scientific expertise. In this respect, I would like to stress that the particularly stringent safety requirements promoted by **> WENRA <** are likely to stimulate research on all reactor types.

Marc Deffrennes — These are unquestionably interesting elements to select and prioritise the research projects to be performed within the frame of the SNETP platform... And all of them were factored in by the TSOs in their position paper on the research needs in nuclear safety for GEN II and GEN III NPPs. Following the events in Japan, there will be pressure for all the prioritised safety issues to be studied in a timely way. This would help the TSOs express their independent judgment. This might then later be taken into account by the EC in activities fostering a greater harmonisation of safety approaches at EU level. ✖

WENRA proposal

At their plenary meeting on March 22nd and 23rd, 2011, WENRA members decided to provide "an independent regulatory technical definition of a 'stress test' and how it should be applied to nuclear facilities across Europe". This is the purpose of the document titled The proposal by the WENRA Task Force about "Stress tests" specifications (21 April 2011). This document is downloadable at www.wenra.org > Publications.

Methods & Organisations



For decades, emphasis was clearly placed on preventing the occurrence of accidents in nuclear reactors. As a consequence, hundreds of units operate safely, year after year, throughout the world. But three major accidents forced the nuclear safety community to reconsider the limits of prevention and to grant accident mitigation and emergency situations management full consideration.

What we did not consider as expectable or reasonably possible did actually happen

Safety engineers working in the industry, in TSOs, etc. have kept refining nuclear safety methods for decades to prevent situations potentially conducive to accidents, particularly severe accidents. But three times in the history of nuclear power, internal or external events triggered accident sequences ending up with a reactor core meltdown. What was wrong with the assessment methods used as a basis for nuclear plant design? Which assumptions should be reconsidered to further improve these methods in the light of experience feedback? The EUROSAFE Tribune asked Giovanni Bruna, Deputy Director, Reactor Safety Division at IRSN.

> "Three Mile Island, Chernobyl and, more recently, Fukushima-Daiichi are here to remind us that internal or external events that were not postulated at the design stage can nevertheless happen and end up in accidents well beyond the design basis!"
>
> Giovanni Bruna
> Deputy Director,
> Reactor Safety Division,
> IRSN

TO START, LET US COME BACK TO BASICS! HOW WOULD YOU CHARACTERISE THE PURPOSE OF SAFETY ASSESSMENT?

In very simple terms, I would say the safety assessment of nuclear facilities – of nuclear reactors in particular – is the identification and, whenever possible, the quantification of the potential risks associated with their construction and operation, including those resulting from environmental conditions, ageing, planned changes in plant design, fuel management, plant operation, etc. and also those resulting from uncontrollable – or uncontrolled – events such as internal and external hazards as well as malevolent acts.

HOW CAN SUCH A WIDE ARRAY OF ASPECTS BE DEALT WITH?

Well, the target is by essence an ambitious one! To achieve it, it is necessary firstly to identify all individual sources of risk and assess

Fuel cycle plants, radioactive materials handling and transport... besides reactors, the safety of all the components of nuclear power generation should be reassessed taking into account highly unexpected events. And this is the responsibility of all the stakeholders.

their potential contribution to the overall risk, then to analyse and understand the underlying physical and chemical phenomena, and also to have thorough knowledge of systems' behaviour and operating procedures with a view to pointing out their weaknesses and possible ways for improvement. This requires a combination of operating experience feedback and of further studies and experiments, which have to take the social and economic context into account, too.

WHAT IS THE CONTRIBUTION OF THE DETERMINISTIC APPROACH TO SAFETY ASSESSMENTS?

As its name shows, the approach consists in the assessment – through deterministic computation – of postulated events that – according to current safety practice – must be practically excluded by design, drawing primarily upon the concept of "defence in depth". This concept relies firstly on a succession of containment barriers aimed at preventing any release of radioactivity to the environment. Nuclear reactors thus have three barriers: the fuel cladding, the vessel and the primary circuit, and the containment building. Defence in depth also relies upon the study of reactors' states – notably transients – and operating conditions, the categorisation of accidents as well as the rules for studying accidents.

THIS DETERMINISTIC APPROACH DIDN'T PROVE SUFFICIENT TO PREVENT SEVERE ACCIDENTS...

Unfortunately, Three Mile Island (TMI), Chernobyl and, more recently, Fukushima-Daiichi are here to remind us that internal and/or external events that were not – or, anyway, not extensively enough – considered at design stage can nevertheless happen and end up in accidents well beyond the design basis! And this is the reason why probabilistic safety analyses were implemented as a complement to the deterministic ones, mostly with the aim to detect the main and most relevant contributors to the overall risk. But let me point out that the deterministic approach remains dramatically valuable to the dimensioning of the barriers and in some specific fields of endeavour, such as nuclear security, as it is very difficult to quantify, in a probabilistic way, malicious acts perpetrated by man.

WHAT IS THE PURPOSE OF PROBABILISTIC SAFETY ASSESSMENTS?

The probabilistic methods are based on as thorough an identification as possible of all the combinations – which we call 'accidental sequences' – of material and/or human failures which could lead to serious consequences. The quantitative assessment is based on reliability data for the components and models for the operators' behaviour provided by operating experience. With the purpose to assess the risk of serious reactor deterioration as a result of inter-

nal events, the probabilistic approach allowed the determination of main families of scenarios with analogies, such as small breaches of the primary circuit, small breaches of the secondary circuit, the dilution of > **Boric acid** < with non-borated water, etc. Then, mitigation measures are analysed quantitatively on a case-by-case basis with a view to assessing the risk of failure and, if any, looking for alternative – generally design-based – countermeasures. A major contribution of the probabilistic approach to safety assessments is the possibility to compare the different families of transients.

TMI

Chernobyl

TMI, Chernobyl, Fukushima-Daiichi: three totally different root-causes conducive to severe accidents with reactor core meltdown.

WHAT DID FUKUSHIMA-DAIICHI TEACH US IN TERMS OF SAFETY ASSESSMENT METHODS?

Unquestionably, the major lesson for us is that what we did not consider as expectable or possible did nevertheless happen: the combination of two successive catastrophic external hazards, i.e. a powerful earthquake followed by a devastating tsunami... and the loss of ground-access ways to the plant in quite hard environmental conditions, with cold and snow. All consequences of a common event: a seism under an ocean. These extreme conditions resulted simultaneously, for the Fukushima-Daiichi NPP, in the destruction of buildings, the accumulation of debris, the loss of electrical power, the loss of cooling of the reactor core and pools... and the inability to bring the situation back to normal because of the devastation, of the very uneasy access to the plant, etc. In terms of safety assessment methods, Fukushima-Daiichi means supposedly impossible – or anyway extremely unlikely – scenarios must now be factored in for evaluating the robustness of the existing reactors and of those under construction or to be built. Concerning particularly the GEN III and GEN III+ reactors, we'll need to perform more comprehensive and more in-depth assessments of external hazards prior to selecting any construction site and, as the experience feedback from Fukushima-Daiichi increases, we'll have to analyse the lessons learned in a holistic way to reassess the priorities in our R&D programmes, as is currently the case with the SNETP task group. In this respect, I think the priority among priorities is to incorporate experience feedback at all times and to work relentlessly on the alignment of safety requirements and practices worldwide!

Fukushima-Daiichi

Fighting nature's and man's uproar

In recent years, new threats pushed safety experts into reconsidering the external and internal loads on NPPs, focusing not only on internal hazards, but also on the destructive power of external agents such as earthquakes and tsunamis, severe weather conditions, explosions, blasts and fire, external dynamic loads and malevolent acts. The SNETP member TSOs deem R&D in this area should address primarily the system's capability to return to a safe state in convenient time, notably by improving the operator's responsiveness through specific preparedness training.

External hazards include all the loads that the environment can charge on a nuclear plant, as a consequence of earthquake, tsunami, flooding, blast, explosion and their combination, which can cause significant damage on the plant's operability, being potentially conducive to severe accidents. The cumulated effects of such external loads include the destruction of buildings and access ways, the debris build-up, the loss of electrical power supply as well as the loss of cooling capacity of the reactor core and the fuel pools. *"The Fukushima-Daiichi NPP accident, the outcome of which is investigated within a specific task group in SNETP's strategic research agenda, is likely to provide additional input for the definition, prioritisation and execution of R&D tasks,"* stresses Piet Müskens, Director-inspector of the Department of Nuclear and Radiological Safety, Security and Safeguards of the Inspectorate of Housing, Spatial Planning and the Environment of the Dutch Ministry for Infrastructure and Environment.

Keeping up with a changing environment

A challenging prerequisite for any effective protection against external hazards is to accurately assess them by adopting the appropriate **> deterministic <** or **> probabilistic <** or combined methodologies, relying on suitable collections of recorded observations. Accordingly, the reliability of the assessment highly depends on the quality and exhaustiveness of the available data. *"The environment that surrounds any NPP is continuously changing for climatic and morphological reasons. Safety studies are therefore affected by increasing*

uncertainties, when focusing on the extreme events – and their possible combinations – which have to be accounted for safety purposes. Accordingly, when assessing the safe behaviour of a system, component or equipment, its robustness and resistance to all kinds of internal and external hazards is to be demonstrated, adopting this penalising combination of loads," Mr. Müskens explains. In this process, the knowledge gained through the studies and the feedback from NPP operation allows continuous updating of the uncertainty appraisal methods, which, in turn, drive the evolution of the safety requirements issued by the regulatory bodies, the design and construction rules adopted by the vendors, as well as the safety assessment methodologies.

Moreover, for decades, probabilistic safety analyses are used to assess the total safety of NPPs for instance expressed as Total Core Damage Frequency (TCDF) of an NPP. More and more scientific reality checks of these TCDFs are asked for. *"Public and politicians are asking for it,"* Piet Müskens says. *"R&D is able to provide the scientific answers and regulatory experts are there to give explanations."*

Two priority areas for R&D

"Hazard-focusing extensive investigation as well as short- and mid-term R&D should address in priority the integrity of equipment and structures, which includes civil engineering works and mechanical equipment," Mr. Müskens emphasises. This can be achieved through:

- The improved understanding of phenomena governing the degradation modes of equipment and structures with a view to anticipating their behaviour and verifying the suitability of maintenance programs and in-service inspections;
- The development of suitable methodologies to assess the structure and component status, e.g. for examinations of metallic components or concrete cracking detection;
- The upgrade of existing methodologies and the development of new techniques for component repair and replacement;
- The accurate appraisal of the consequences of industrial obsolescence that affect the "as-originally-designed" operability of systems.

Moreover, issues related to electricity infrastructure should be addressed – even if they are not specific to the nuclear industry – as they may jeopardise the safe and secure operation of current and future NPPs through the loss of external power supply and the ultimate heat sink. *"Another priority field for investigation pertains to fire and smoke protection,"* declares Piet Müskens *"and this translates into six main R&D directions"*:

- *Fire detection:* development of non-intrusive investigation of the flame diffusion under the effect of gravity and the pyrolysis of materials;
- *Fire growth and propagation:* development of predictive methodologies enabling and supporting the simulation of the fire propagation in a confined and vented environment, including extreme conditions;
- *Smoke and heat propagation:* development of large-scale integral simulation models;
- *Fire sectorisation elements:* knowledge improvement regarding the passive elements of sectorisation (walls, fire doors, dampers, openings) as well as the consequence from the cumulative effects of a fire (mainly thermal stress, overpressure, humidity);
- *Equipment vulnerability:* assessment of equipment resistance to fire through definition of codes and standards as well as specific product-oriented R&D;
- *Computational capacity and modelling:* regarding in particular the generation of soot and unburned materials in a confined environment, the mechanisms of heat transfer though radiation, and turbulence.

An expert view on malevolence

"There are many possibilities to perpetrate malicious acts, from the inside as well as from the outside of nuclear facilities. The so-called "internal threats" address the consequences of malevolence by a person working in a facility, thus having a good knowledge of its operation. I think R&D performed in this area should focus on the methodological aspects of the assessment of the various scenarios and of their consequences to propose means aimed at limiting the potential damages from such internal threats. This should include the assessment of computer system vulnerabilities that could be used to perpetrate a malicious act. Concerning the so-called "external threats", explosions, blasts, airplane and missile crashes are the main items for R&D programmes, which should address not only materials, but also structures such as the containment and the supports. As far as airplane crashes are concerned, the R&D activity should be focused on reproducing impacts, both theoretically, through appropriate simulation, and experimentally. To me, such programmes are to be carried out primarily as part of international collaborations."

Seppo Vuori
Senior Principal Scientist at VTT
The Finnish TSO is a member of ETSON

3 questions to...

Seppo Vuori

on human and organisational factors

Senior Principal Scientist at VTT, the Finnish TSO, and member of the group of TSOs within SNETP, Seppo Vuori explains the reasons why Human Factor is widely considered as a central issue in the improvement of nuclear safety.

Why is Human Factor a particular domain of consensus among the SNETP stakeholders?

Experience shows that man and organisation play a major role in safety throughout the life cycle of nuclear facilities, during operation of course, but also at the design, construction, modification and dismantling stages. This is why, I guess, human and organisational factors are now increasingly considered as a domain where safety and plant performance are synonymous. Indeed, the nuclear community has to cope with a lot of challenges in the operation of existing plants and the design of new ones. Challenges such as new technology, modernisation programmes, organisational changes, design of advanced reactors, changes in staff and competences, evolution of requirements and regulation, etc. all have an influence on how man and organisations may work safely in the daily operation of plants and manage all kind of situations, including unanticipated ones. In this respect, I think people with a high level of education and experience contribute to the safety of nuclear plants, notably by minimising transients. This is why, in Finland for instance, VTT and Fortum developed jointly a simulator to train engineers in reactor operation. This is also why international co-operation is thriving, with several common projects carried out at EU level and also at OECD/NEA level, notably in the research reactors located at Halden, Norway.

In terms of support to operators, in which areas is progress particularly noticeable at the moment?

To enhance human performance and reliability, plant operation improvement projects are focusing on simplifying operating procedures and providing appropriate operator support. This can be achieved thanks to numerical simulation and high performance computing, which allow visualising phenomena as they occur in the circuits. Fast-running simulation can also provide operation with efficient decision-making support. To improve communication among staff in different situations, thus reducing the risk of mistakes or misunderstanding, systems such as the Radio Frequency Identification, for instance, could help checking on-line the relevance of actions performed by operators.

What is the objective of a safety-oriented human and organisational factor R&D programme?

I think it is to develop, manage and store extensive knowledge in support of the safety and radiation protection expertise in a wide range of topics related to individual, technical and organisational characteristics. Human and organisational factors therefore most often need multi-disciplinary approaches to deal with, and in their position paper, the TSOs participating in SNETP have proposed research topics involving disciplines such as ergonomics, psychology, sociology, anthropology, risk management as well as management sciences, economics, etc.

Towards new challenges

For decades, nuclear safety research relating to the design of nuclear facilities and the amount of knowledge gained has been such that nuclear engineers thought they already knew quite a lot of important aspects about the physical and chemical phenomena that can occur in a nuclear facility, both in normal operation and during accident conditions. The requirement to include the possibility of a severe accident in the design of new plants and, as far as reasonably possible, strengthen the existing plants resistance to severe accidents has highlighted the need for research going far beyond the limits once considered satisfactory for design and operation. So, where are the new frontiers? A question debated between Jean-Pierre Van Dorsselaere (IRSN), and Giovanni Bruna (IRSN), two members of the Sustainable Nuclear Energy Technology Platform (SNETP) and Lars Skånberg (SSM) as a regulator.

Jean-Pierre Van Dorsselaere
SARNET Co-ordinator of the SARNET network
IRSN

Research programmes on severe accidents are long-run programmes due to the particular complexity of the physical and chemical phenomena to be factored in. We must be aware that these phenomena are, in a certain way, beyond 'standards' and that they are reaching extreme values in terms of parameters such as irradiation and temperatures, ranging for example from ambient temperatures to fuel meltdown. This is why the research programmes performed to date e.g. on the release, transport and long-term behaviour of fission products, have allowed significant progress, but remain insufficient to truly benefit from the knowledge gained. Let me take an example: we are capable of computing the **> source term <** at Fukushima-Daiichi, but we still need to reorientate the further R&D work to be capable of determining the appropriate countermeasures in order to mitigate the spreading of radioactive material outside the plant!

Lars Skånberg
Head of Section, Reactor Technology and Structural Integrity, Dept. of Nuclear Power Plant Safety
SSM

Well, Jean-Pierre, I would even say this is also the case for the entire knowledge pertaining to hydrogen build-up, even if we think we already know quite a lot of the process. Now we need to get more detailed information on what really happened in the Fukushima-Daiichi plants and then refine existing models much further to really understand the processes leading to hydrogen build-up, accumulation and blasting. In this respect, I must say the Fukushima-Daiichi accident revived the debate on hydrogen build-up

through radiolysis in pools, a phenomenon that can be completely different from what happens in the reactor primary circuit.

Giovanni Bruna
Deputy Director,
Reactor Safety Division
IRSN

In this regard, I think it really makes sense to devote time and resources to studying all these complex phenomena, since severe accidents have to be considered from the design phase of new reactors, may it be Gen III or Gen IV. This implies more in-depth knowledge of these phenomena to be gained, since such data as the source term are to be considered to dimension the fission product containment functions. The behaviour of > **corium** < inside and outside the reactor vessel is to be accurately assessed, too.

> “To comply with the safety objectives set by WENRA for Gen III reactors, we'll need to reassess all the levels of defence-in-depth as well as the physics of the associated events to push back the limits in terms of probability and consequences of an accident.”
>
> Lars Skånberg
> Head of Section,
> Reactor Technology and
> Structural Integrity,
> Dept. of Nuclear Power
> Plant Safety, SSM

Jean-Pierre Van Dorsselaere

May I point out that all above phenomena are a central topic among the subjects considered in the > **SARNET** < work programme! For instance, while studying the fuel damage processes, in particular the situations of reflooding of a severely damaged core, we perform experiments to measure the heat exchanges with a two-phase coolant flowing through a bed of debris. These are tricky issues, which require new modelling to be developed if we want to predict the behaviour of fuel accurately from a qualitative and quantitative perspective. More generally, large efforts must continue to be put for the improvement of numerical simulation codes of the severe accidents. Note that an uncertainty may remain on the knowledge of the very detailed geometry of the plant and on its real state at the time of accident, e.g. the status of valves or doors in a containment building.

Lars Skånberg

I fully agree with you on the necessity to carry out such studies and, and more generally, the experience of the Fukushima-

The main open issues in severe accident R&D

(as ranked in SARNET)

The release, transport and long-term behaviour of fission products
- The chemistry of the fission products and aerosols in the primary circuit and in the containment (mainly iodine and ruthenium species).
- The long-term behaviour of fission products in the containment and the measures for mitigation of the source term.

The hydrogen production, accumulation and deflagration and the measures to counteract

The behaviour of molten fuel in the reactor core, vessel or pool
- The damaged core behaviour and stabilisation, including the formation of the corium (molten core).
- The in-vessel and ex-vessel coolability of the corium (the former with respect to retention within the vessel).
- The fuel damage in the spent fuel pools and the associated accident progression and its consequences, in particular for the source term.

Daiichi accident and the stress tests now being conducted in Europe and in other countries may affect both the safety assessments and the views on actions needed to be taken in existing facilities to further increase the safety level. Even the design of the new Gen III reactors may be affected.

Jean-Pierre Van Dorsselaere: Definitely! One should not forget the Gen III reactors presently at design phase, as they will incorporate responses to all levels of > **defence-in-depth** <, thus requiring investigation of a much wider panel of accidental sequences.

Lars Skånberg: Regarding preparedness for severe accidents, experience gained from the Fukushima-Daiichi accident so far shows that the starting points and assumptions for the design of national severe accidents management and protection measures may need to be reassessed. TSOs have an important role in supporting the authorities responsible in different areas of society, both as experts organisations and in the work to further develop methods and tools that can be used in the accident management and protection context.

Giovanni Bruna: Let me add that the recent event in Japan has demonstrated that a country cannot face a wide-scale disaster alone. In this situation, relying on the possible support from other countries is of utmost importance. Moreover, in the longer term, a high standard of emergency preparedness and management has to be kept, should resources decrease with time. I think it is therefore essential to develop a European platform as a support to decision-making and emergency management. This platform could notably propose scenarios for the planning, performance and evaluation of exercises, contributing to strengthen the preparedness and planning as well as to keep competences in this area. This objective should gather all the actors of the nuclear field, including the stakeholders and the general public. ✖

Science & Technology

"Theoretical and experimental research is carried out with a view to understanding in as an accurate way as possible the physical and chemical phenomena occurring notably inside the fuel during the transients of a reactor's operation, from full to low power to shutdown. To go beyond the present design-basis limits, the complexity of the phenomena is such that it requires a multi-physics approach of research."

Andreas Pautz
Head of Reactor Safety Research Division, GRS

Fit for purpose?

Severe accidents have to be practically excluded by design and mitigated by safeguard systems over the entire operation lifetime of nuclear power plants. This principle, which supports the safety demonstration of advanced plants, is likely to be extended progressively to the plants in operation with a view to achieving fully aligned operation of the different reactor fleets in terms of safety. At a time where several operators consider extending the service lives of some of their plants, ageing represents a major challenge in this regard, as it encompasses not only materials but also design, organising, etc.

An expert's view

Obviously, the exclusion of severe accidents can be demonstrated relying upon dependable design options, robust numerical computations and improved component technology. But it relies also – and mainly – on the ability to detect early any failure or threat that could challenge the integrity of the barriers. In the latter case, the improvement of methods and techniques for inspection, maintenance and repair, taking into account notably ageing, is likely to require new and specific R&D efforts in different fields to ensure that the basic rules of the safety demonstration are still satisfied all along the NPPs' life cycle if their operation lifetime is to be extended, as targeted by several utilities. Industrial players will lead the programmes, but we are of course interested in understanding the different methods they intend to implement. Moreover, some research projects could be launched by the NULIFE network as part of the FP7, or under complementary initiatives by NULIFE partners, or could be driven by TSOs independently from the industry. In any case, increasing openness and transparency of all safety research is needed.

Rauno Rintamaa
Vice President, VTT
VTT is a member of ETSON

Ageing is a multifaceted issue and its successful management requires at least a common understanding of different questions, starting with the ageing mechanisms of materials and components, a pivotal concern that can result in both theoretical investigations and experimental programmes, conducted through an enlarged network of international collaboration. Other success factors are the development of dedicated computation tools and advanced multi-scale computation code systems drawing upon the knowledge gained from previous experience, the implementation of component properties suited for a long-term operational perspective, as well as the harmonisation of practices.

Identifying not only the thresholds but also the precursor state

"From a TSOs' perspective, significant improvements are necessary in the physical understanding of all relevant ageing mechanisms and their driving parameters," claims Yuri Alekseev, Head of Department of Thermal-Hydraulic Analysis at ARB SSTC, the Ukrainian TSO which became an associated member of ETSON. *"Our goal is to become able to anticipate such mechanisms, including those either fully ignored or deemed of low importance in the current plant opera-*

tion perspective, as is the case today with creep and thermal ageing for instance. We think it is worth identifying not only the thresholds for the initiation of defects and the kinetics for their propagation, but also their precursor state. That would allow an early detection of potential degradations and an efficient mitigation of the ageing consequences," he goes on.
With this purpose, priorities for investigation are presently identified by the SNETP member TSOs, such as corrosion (e.g. stress corrosion cracking), concrete ageing, fatigue, irradiation effects, material embrittlement, stainless steel cracking in stress conditions, creep or thermal ageing. The corresponding knowledge should be gained from analytical experiments and operating experience feedback as well as from numerical simulation. *"This calls for modelling fundamental phenomena in physics and chemistry, at different scales, from atomic to macroscopic level, to ensure reliable long-term predictions of ageing and its effects,"* Yuri Alekseev concludes.

> "The industry's know-how related to component characteristics is essential for the TSOs involved in ageing assessments."
>
> Claus Verstegen
> Head of Plant Operation Division GRS

Learn more about... NULIFE

Nuclear plant life prediction (NULIFE) is a European network of excellence launched with a clear focus on the sustainability of nuclear power as well as on the continued and safe operation of current nuclear power plants over 60 years or more. The importance of the long-term operation of the plants has been recognised at European level, e.g. in the strategic research agenda of SNETP. NULIFE brings together over 50 partners from leading research institutions, technical support organisations, power companies and manufacturers throughout Europe.

www.vtt.fi > Publications > Nulife

3 questions on...

Instrumentation & Control systems

Head of the Nuclear Installation Safety Laboratory at the Lithuanian Energy Institute (LEI), and member of the group of TSOs within SNETP, Sigitas Rimkevičius expresses views on the specific safety issues related to electrical Instrumentation and Control (I&C) systems and the ways to square the circle through safety R&D.

Why are electrical Instrumentation and Control (I&C) systems considered as particularly safety-critical?

I&C systems provide the NPP operation with the necessary control, protection and safeguard capability in any normal or degraded operation as well as accidental circumstance. They are thus pivotal to the plant safety through their contribution to the defence-in-depth approach and the practical elimination of severe accidents.

What are the major challenges associated with the safety assessment of I&C systems?

As they become increasingly sophisticated, digital systems can neither be deemed flawless in terms of programming nor be exhaustively tested. To circumvent this difficulty, widely industrialised components are used, considering that their reliability increases with the number of end-users. But since they are already commonly used, such components become rapidly obsolescent... Another problem is linked to the classification of reactor systems according to their required level of safety: in principle, at each level of safety, the reactor systems concerned should be controlled by independent I&C devices offering the same level of safety. But by selecting off-the-shelf commercial I&C systems, we create unintentionally a common mode failure, since all the reactor systems – even the most safety-critical ones – are controlled by I&C offering the same level of safety, in complete contradiction with the principles of reactor systems classification. Last but not least, ageing threatens the electrical and electronic components of the control, safety and safeguard systems, thereby increasing their probability of failure.

What can be done to qualify innovative I&C systems?

Today, TSOs perform as exhaustive testing as possible on new designs of I&C systems, but this obviously does not solve all the problems, notably in the event of an accidental sequence in a nuclear reactor. Therefore, the TSOs within SNETP propose R&D initiatives aimed at allowing I&C qualification for harsh accidental and post-accidental environmental conditions such as vibration, temperature, pressure, jet impingement, radiation, humidity, etc. The TSOs also call for complex systematic analyses and multi-disciplinary efforts to implement consistent equipment qualification programmes based notably on a clear understanding of the environmental parameters which influence I&C ageing as well as on the anticipation of the new challenges and the follow-up of technological innovation. In this respect, we think a common approach should be developed either to create obsolescence-resistant technologies, possibly with other industries, or to adapt nuclear procedures to even faster evolving domains, vendors using more and more off-the-shelf technologies and components.

TECHNICAL ZOOM

In order to limit the run-time requirements, system codes widely adopt simplified representations of flow characteristics. As a result, in many cases, they are neither scalable nor adaptable in geometry.

Multi-physics are key to modelling complex phenomena with accuracy

Utilities use increasingly sophisticated methods and codes to demonstrate that a reactor still satisfies the prescribed safety limits considering enhanced performance, components ageing and better physical modelling. In particular, describing the complex physical and chemical phenomena that occur during transients or accidents requires advanced computer hardware as well as sophisticated software design to allow the coupling of thermal-hydraulics, thermal-mechanics, reactor physics, and overall system response. Such coupled code systems require extensive verification and validation efforts. In order to limit the run-time requirements, system codes widely adopt simplified representations of flow characteristics. As a result, in many cases, they are neither scalable nor adaptable in geometry. Consequently, to be sure that the phenomena and uncertainties are correctly addressed and the safety criteria fully satisfied, the codes need further development. In the near future, investigations of very local and/or highly complex phenomena, such as the flow stratification in pipes and tees or the local double-phase phenomena in case of LOCAs are expected to rely more and more on Computational Fluid Dynamics (CFD) techniques to complement the conventional tools and obtain more precise physical descriptions.

New tools for better accuracy, increased computing efficiency and user-friendliness

Single-phase CFD applications are already reasonably mature, although some models need improvement, but two-phase and multi-phase CFD

Learn more about... NURESIM project

An FP6 project involving 13 European countries and 18 partners, the European Platform for Nuclear Reactor Simulations (NURESIM) project is aimed to provide the initial step towards a Common European Standard Software Platform for modelling, recording and recovering computer data for nuclear reactor simulations. Such a common platform would also facilitate the exchange of data across sites, application codes and computing platforms.

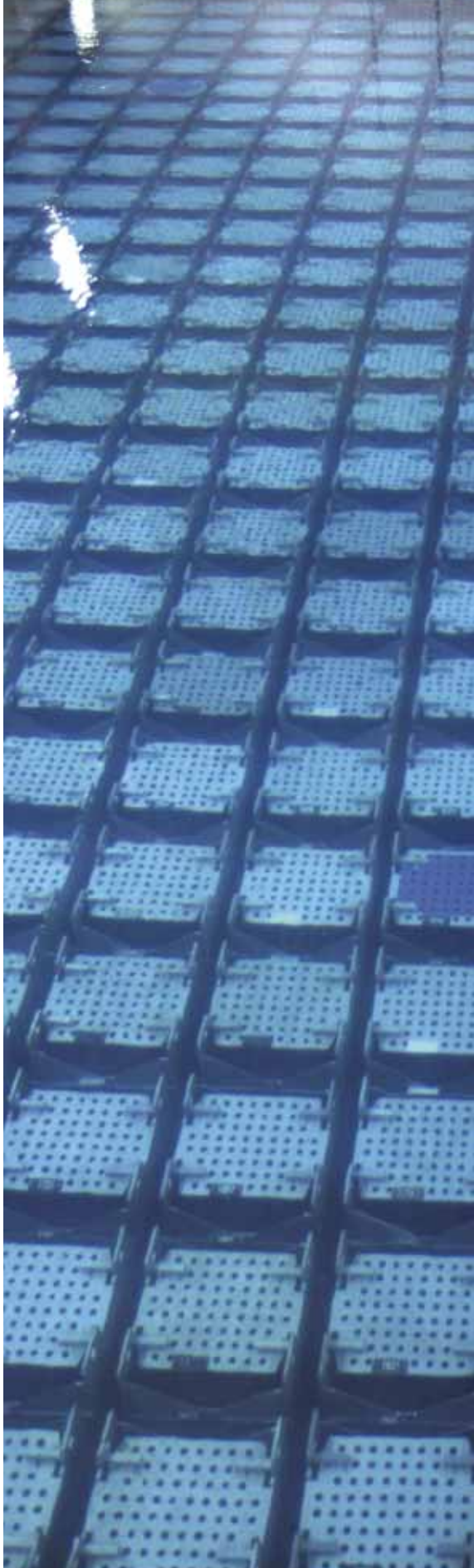
www.nuresim.com/

modelling still require R&D efforts. Subsequently, the implementation of suitable CFD techniques will be a major R&D challenge in the short/mid term which can largely benefit from the progress of advanced numerical simulation. It will undoubtedly provide users with an extended capability to calculate local parameters and consequently allow a better understanding of the physics, which should end in more reliable designs, reduced costs and/or precisely quantified safety margins. For the evaluation of the operation and safety of current and future (GEN III) reactor designs, new tools are expected to offer better accuracy, higher computing efficiency and increased user-friendliness. In this respect, an increased need for research is expected to sustain the production of:

CFD techniques will undoubtedly provide users with an extended capability to calculate local parameters and consequently allow a better understanding of the physics.

- tools that are experimentally validated for a large part;
- best-estimate simulation tools for the modelling of thermal-hydraulics and core physics phenomena;
- suitable methodology for predictive estimation of errors.

A first step in this direction has been undertaken by the NURESIM Integrated Project, which has started the development of a European reference simulation platform for nuclear reactor applications, with a focus on PWR, VVER and BWR. NURESIM is to continue with FP7 projects such as the Nuclear Reactor Integrated Simulation Project (NURISP) aimed to consolidate and extend the platform, and ultimately with NURENEXT, aimed to confirm, rationalise and further extend the platform.



Nuclear fuel: a safety concern from cradle to grave

Fuel behaviour in normal and degraded conditions is currently – and will continue to be – a major issue for the safe and profitable operation of NPPs. These past years, new reactor core designs, advanced loading strategies as well as more flexible operating modes have been implemented by utilities. As a result, nuclear fuel is operated at ever more aggressive conditions, calling for enhanced fuel robustness and reliability to accommodate e.g. higher uranium enrichment and plutonium recycling, higher burn-up, power upgrades as well as increased lifetime and cycle length. As a consequence, the safety criteria established for fuel in the 60s and 70s are being reviewed, bringing to light pending R&D issues. A difficulty in this area pertains to industrial secrecy, as modelling fuel performance strongly relies on proprietary data. Thus, sharing knowledge and development turns out quite difficult. However, collaborative work in the area of LWR fuel behaviour is very active and benefits from international research programmes.

Among the main pending safety-related R&D issues with respect to nuclear fuel, a particular effort is to be put on clad ballooning and fuel relocation, as it can affect among others the short- and long-term coolability of the reactor core, and the source-term aspects in case of a **> LOCA <** and **> RIA <**. *"Collaborative work has been performed in the past to assess the LWR fuel behaviour in accidental conditions; this work is planned to continue,"* claims François Barré, Head of IRSN Department of Fuel in Accident situations, *"current development efforts mainly address the fuel rod modelling during a LOCA and RIA, accounting for fuel fragmentation and relocation, clad stress and ballooning, clad rupture, ejection of fuel fragments, and possible under-cooling. Advanced representation of the thermo-mechanics of the fuel rod and even a representation of the whole fuel assembly are believed necessary, in particular for LOCAs and Spent Fuel Pool accidents, for a reliable simulation. One of the key issues to be solved is also to properly couple the existing thermo-mechanics basis with adequate thermo-hydraulics models representing the very specific behaviour of the coolant under both RIA and LOCA situations."*

Going on with theoretical research and experiments

The fuel rod behaviour over time scales from milliseconds to years is predicted by 2D fuel performance codes, while more detailed models, including 3D approaches at very local scale,

are available to predict some specific aspects like fission gas behaviour, fuel fragment relocation or crack propagation in the cladding. To achieve a complete multi-scale simulation, the current methodology needs to be complemented with more detailed techniques such as **molecular dynamics** for the fission gas behaviour or cohesive zone models for cracking of materials. *"This process has already been launched in some organisations such as IRSN during the last years,"* François Barré points out. Besides modelling, the experimental research programmes on thermal hydraulic aspects and on fuel behaviour mainly under LOCA or RIA conditions should be continued, relying on international networking as well as on dedicated experimental facilities, such as the Nuclear Safety Research Reactor of the Japan Atomic Energy Research Institute, the Halden research facility in Norway, and the CABRI facility in France.

> "Current industrial issues for fuel are advanced loading strategies, operating modes intended to provide greater flexibility, technological improvements on cladding materials with new alloys and on fuel pellets with different types of MOX, doped and large-sized grain fuels, short fuel pellets, etc. Today's fuel safety issues have little to do with what they used to be a decade ago."
>
> François Barré
> Head of Department of Fuel in Accident Situations
> IRSN

Fuel handling: a multifaceted safety issue

From fabrication to disposal or recycling, fuel is handled at each stage of its life cycle, bringing about safety problems especially related to the risk of criticality and degradation potentially conducive to the release of radioactive material to the environment. *"Knowledge of the steps that can lead to criticality accidents is necessary to assess the safety of the nuclear fuel cycle, optimise the detection of such accidents, and be prepared accordingly,"* explains Vincent Deledicque, R&D co-ordinator at Bel V. *"In this respect, the qualification of the numerical codes used to describe fuel behaviour is essential, and more complete experimental campaigns, such as the one performed during the MIRTE programme, as well as theoretical work in a detailed modelling of neutron behaviour should be sponsored in order to improve numerical codes,"* he claims.

Concerning spent fuel, the removal of residual heat over a long period of time is a source of specific concern. In this area, the validation of new passive heat removal systems based on natural convection relies upon the use of complex 3D thermo-hydraulic codes to account for instabilities that could, for example, prevent natural convection. Another challenge is linked to the rearrangements aimed at increasing the quantities of fuel stored in cooling pools, as several nuclear power plants are currently reaching their storage limits. Such modifications have to be performed, taking into account the fact that fuel assemblies themselves have become more reactive and that the neutron absorbers installed in the pools to comply with criticality requirements have exhibited some degradation. Reflecting the TSOs' views, Vincent Deledicque emphasises: *"Safety reasons justify improvements in the design and modelling of the spent fuel pools, with special attention to the aforementioned concerns. The Fukushima-Daiichi events also motivate better prediction capabilities of the consequences in such systems during accidental conditions".*

Last but not least, the management and final disposal of nuclear waste needs further significant research efforts. Firstly, possibilities for waste volume reduction are examined, considering several conditioning methods or even transmutation to shorter-lifetime products. Secondly, deep geological disposal concepts based on a multi-barrier system that contains and isolates the radioactive waste from the biosphere are studied for disposal of long-lived waste products. In order to gain confidence in the long-term capabilities of such devices, research is still required in several domains such as waste degradation, the long-term degradation of engineered barriers as well as radionuclide geochemistry and migration. *"The studies going on at experimental research facilities such as* **Tournemire** *in France or* **Hades** *in Belgium for example should help TSOs in the global safety assessment of deep geological repositories,"* Mr. Deledicque concludes.

Special Focus

Synthesis on Fukushima-Daiichi lessons

IRSN's Emergency Response Centre, set up immediately after the earthquake and subsequent tsunami stroke the Fukushima-Daiichi power plant.

With the safety of workers and the public at large as an ultimate goal, and in compliance with their missions at a national level, the TSOs are developing their competences through education, research, operating experience feedback and knowledge management in order to provide the national safety authorities with state-of-the-art expertise. Their job also includes the consideration of potential new risks and the provision of proposals aimed at developing the necessary competences accordingly. TSOs clearly express the wish to develop synergies in order to enhance and carry out the necessary research programme in the safety field, to encourage the technical debate and enlarge the scientific domain that enjoys consensus, hence focussing on the safety issues that are still subject to debate among the stakeholders.

Going beyond design-basis limits

Nuclear safety is the business of all stakeholders

New players emerge across the globe both on the offer and on the demand sides, making the nuclear power industry a definitely international one, just as are aeronautics or electronics. From a safety assessment viewpoint, this implies the assessment methods and research projects to be shared with a consistent approach. *"This is why the TSOs felt the need to work more and more together, not only to develop assessment methods, but to carry out safety research projects jointly,"* declares Vincent Deledicque, R&D co-ordinator at Bel V, the Belgian TSO. Year after year, it became obvious that nuclear safety is the business of all stakeholders – TSOs and regulators of course, but also industrial manufacturers, utilities and research centres – and that pooling safety research develops an area of technical consensus without compromising the independence of safety assessment by the TSOs, as highlighted by Edouard Scott de Martinville, Head of the International Relations Delegation at IRSN, the French TSO: *"As European NPP designers and operators are also committed to developing energy systems with the highest safety standards, they may share a large part of existing and future research proposed by the TSOs."*

> "One consequence of the Fukushima-Daiichi accident for safety research is the requirement to be able to know the best-estimate behaviour of the plant systems up to beyond-design-basis accidents."
>
> Edouard Scott de Martinville
> Head of the International Relations Delegation
> IRSN

Promoting well-balanced safety research priorities

The belief of the SNETP member TSOs is that their position paper will largely contribute to the prioritisation of research: *"It becomes obvious that safety research experts involved in SNETP might be overwhelmed with work, for the EU wishes a large part of the resources dedicated to SNETP to be focused on safety, as evidenced by the orientations of the 7th Framework Programme (FP) in the domain of fission technology and probably also of Horizon 2020, the programme set up to take over from the 7th FP,"* Edouard Scott de Mart-

inville goes on. In this context, an important benefit is expected from SNETP to promote well-balanced priorities, even if each single stakeholder's priorities may differ, when analysed in details. *"Were TSOs' research programmes not supported by other stakeholders, it would be useful to consider the potential cost of a badly-managed severe accident induced by design weakness, operation error or severe external hazards: responsibilities of all stakeholders would be involved, including safety organisations!"* warns Vincent Deledicque.

The lessons learned from the Fukushima-Daiichi accident

The accident was triggered by a largely beyond-design-basis external load compounding a magnitude-9 tremor and a subsequent huge tsunami. Despite the outstanding experience and expertise of Japanese organisations to cope with earthquakes, the level of the March 11th, 2011 hazard was such that it challenged several lines of defence, destroying some of them simultaneously (e.g. the main and back-up electrical power supply, the ultimate heat sink, etc.).

In terms of *crisis management*, it appears that the main difficulties in dealing with the Fukushima-Daiichi accident resulted firstly from the necessity to manage at the same time the population and the reactors hit by the earthquake and the resulting tsunami, secondly from

An expert's view

As regards the lessons learned in nuclear safety, as suggested in the Japanese Government's reports to the IAEA Ministerial Conference and the IAEA General Conference, this accident calls for, among other things, extending the defence-in-depth safety approach to any type of hazard that may arise, in particular the external hazards; considering the defence against beyond-design-basis accidents in any case of hazard; and developing more independence between the different lines of defence with respect to 'beyond-design' hazards. Regarding crisis management, the simultaneous involvement of four NPP units obviously overwhelmed the human capacity of the crisis management team and the means available. Therefore, some experience feedback has to be performed on that specific point. In addition, it is also important to take opportunity of possible support from other countries. In order to be effective, this foreign support must not disturb the national organisation, but should be driven carefully into the national organisation. This support capability implies the crisis management to be sufficiently applicable to the different countries in terms of organisation, technical communication, management methodology and scientific calculation tools.

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JNES is an associated member of ETSON



the simultaneous accident in four units and the associated fuel pools (the status of each unit making it more difficult to care for the neighbouring ones), and thirdly from the lack of any rapidly available backup supply of electric power and coolant.

The stress tests performed on the operating reactor fleet: another outcome from March 11th

Checking the safety level of existing plants, this is the aim of the stress tests defined with the participation of all the stakeholders in the nuclear industry. *"In this area, the members of ETSON consider the WENRA proposal as the reference definition for such tests,"* Vincent Deledicque recalls, *"Those tests are suitable to reveal weaknesses in man and technology when NPPs are submitted to extreme conditions such as earthquakes, flooding, loss of electrical power and loss of heat sink."* They are expected to provide lessons to develop new policies in safety philosophy and safety research.

Turning lessons learned into decision-making: ETSON initiatives

Once again, the Fukushima-Daiichi accident clearly shows that, when it comes to nuclear energy, an accident anywhere is an accident everywhere. Up to know, the very first lessons learned pertain primarily to crisis management, but further scientific research on reactor safety will unquestionably appear necessary in the longer run, once an accurate assessment of the status of each damaged reactor has completed. *"May I recall that the examination of the damaged reactor core at Three Mile Island could start only five years after the accident!"* Edouard Scott de Martinville stresses. However, the lessons already learned in terms of assessment methodology – such as the extension of the defence-in-depth concept for instance – will be conducive to new research, aimed notably at gaining knowledge on the behaviour of facilities under "beyond-design" strain.

One consequence of the Fukushima-Daiichi accident for safety research is the requirement to be able to know the best-estimate behaviour of the plant systems up to beyond-design-basis accidents.

With this in mind, the European TSO network has decided to launch two simultaneous initiatives. The first one is an alignment of crisis management approaches including technical information sharing,

measurement of emergency staff and population radiological exposure, environment monitoring and cartography, decontamination methods, and – last but not least – the management of contaminated waste. The second initiative is an improvement of safety expertise methods based notably on provisions (see box) pertaining to the definition of objectives, the performance of assessments, the building of skills, etc.

Research programmes to open new prospects

In the safety area, the design of nuclear power plants aims at demonstrating the existence of margins with respect to reference scenarios. *"In this regard, one consequence of the Fukushima-Daiichi accident is the requirement to be able to know the best-estimate behaviour of the plant systems up to beyond-design-basis accidents. Also, it is worthwhile to know when the behaviour of the system is continuous with respect to the intensity of stress applied, and when the behaviour is becoming non-linear or catastrophic. This may call for a large extension of the physical modelling and computer tools development in different areas,"* Vincent Deledicque prophesises. An unprecedented initiative by its scale, the TSO's safety research programme will be reviewed on a regular basis every two years and also depending on the experience feedback from the Fukushima-Daiichi accident.

Seven provisions to further improve safety

① Agree at an international level about the high-level safety objectives to be complied with; for example, generalise the application of the WENRA objectives.

② Examine the different possible designs at a multinational level up to the issuance of a common design certification. This could be examined in a process similar to the MDEP: in practice, it requires harmonisation of safety objectives and licensing processes among all stakeholders.

③ Adopt a common policy to propose only such certified reactor designs on the international market, while protecting the intellectual property of the designs.

④ Generalise the stress test definition to be applied to all NPPs throughout the world.

⑤ Harmonise the assessment methods of the NPPs' safety level.

⑥ Elaborate common standards for skill building and staffing in NPP safety.

⑦ Extend, on the Nuclear Safety Standards side, the application of defence-in-depth to any hazard, adding the "beyond-design-basis" behaviour with a view to mitigating its effects.

Glossary

Boric acid
is used in nuclear power plants as a neutron absorber to slow down the fission rate. Changes in boric acid concentration allow regulating the rate of fission taking place in the reactor.

CHIP
Conducted by IRSN in partnership with the French National Centre for Scientific Research (CNRS) as well as the Finish Research Institute VTT, the CHIP programme aims to reduce the level of uncertainty on radioactive iodine releases during a core meltdown accident in a nuclear reactor. Its results will also be used to better define the means and measures to be implemented in order to limit such releases.

Corium
Molten mixture of nuclear fuel, fission products, control rods, and structural materials from the affected parts of the reactor, products of their chemical reaction with air, water and steam, and, in case the reactor vessel is breached, molten concrete from the floor of the reactor room.

Defence-in-depth
Practice of having multiple, redundant, and independent layers of safety systems to reduce the risk that a single failure of a critical system could cause a core meltdown or a catastrophic failure of the reactor containment.

Deterministic approach
This approach aims to ensure that the various situations, and in particular accidents, that are considered to be plausible in a nuclear power plant, have been taken into account, and that the monitoring systems and engineered safety and safeguard systems will be capable of ensuring the containment of radioactive materials. It is based on two principles: leaktight barriers and the concept of defence-in-depth.

ETSON
The European Technical Safety Organisations Network (ETSON) members are Bel V (Belgium), GRS (Germany), IRSN (France), LEI (Lithuania), UJV (Czech Republic), VTT (Finland) and VUJE (Slovakia). The two associated members are JNES (Japan) and SSTC (Ukraine). Together with CSN (Spain), KFD (Netherlands) and SSM (Sweden), they constitute the membership of EUROSAFE.

Hades
An underground laboratory situated in Boom clay and operated by SCK•CEN in Mol, in the province of Antwerp, Hades is the most important infrastructure in Belgium for experimental research on the deep geological disposal of radioactive waste.

LOCA
A loss-of-coolant accident (LOCA) is a nuclear reactor accident during which the heat removal from the reactor core is impaired and that can result in reactor core meltdown.

Molecular dynamics
is a computer simulation of physical movements of atoms and molecules.

PHEBUS PF
A Euratom Framework programme, the Phebus-FP Programme comprises 6 integral experiments on reactor severe accidents dealing with fuel degradation, fission product release, transport and behaviour in the containment. Its ultimate goal is to provide insight on the applicability of severe accident codes to real situations, and to help disseminate the knowledge acquired throughout the European and international community.

Probabilistic approach
Probabilistic safety assessments are used to calculate the probability of damage to the core as a result of sequences of accidents (level 1), assess the size of radioactive releases from the reactor building in the event of an accident (level 2), as well as the impact of such releases on the public and the environment (level 3).

RIA
A Reactivity Insertion Accident (RIA) is a nuclear reactor accident that involves an unwanted increase in fission rate and reactor power, potentially conducive to severe damage of the reactor core.

SARNET
A network of excellence federating European research on severe accidents in nuclear power plants, SARNET aims at improving knowledge on severe accidents in order to reduce the uncertainties on the pending issues, thereby enhancing plant safety; co-ordinating research resources and expertise available in Europe (plus a few non-European major players); preserving the research data and disseminating knowledge.

Source term
Expression of the type, quantity and kinetics of radioactive product releases from a nuclear facility during normal or accidental operating conditions.

Tournemire
Experimental research facility operated by IRSN in the south of France to study the behaviour of argillaceous rock layers from the perspective of long-term safety of the deep geological disposal of long-lived, high-level radioactive waste.

WENRA
A network of chief regulators of EU countries with nuclear power plants, WENRA aims at developing a common approach to nuclear safety, providing an independent capability to examine nuclear safety in applicant countries, exchanging experience and discussing significant safety issues.

The editors would like to thank the contributors to the Position Paper of the Technical Safety Organisations titled *Research needs in nuclear safety for GEN 2 and GEN 3 NPPs* for their valuable support to the present issue of the EUROSAFE Tribune.

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