Research for the safety of existing nuclear facilities

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Abstract:
The essential role of research for maintaining the high safety standard for the existing nuclear installations is outlined in the context of internationally agreed needs. The three co-authoring Technical Safety Organisations are committed to continued safety research, recognising operational experience and new technologies as the main driving forces. The safety margin concept is introduced and new trends in traditional and new areas of safety research are identified. The importance of a sufficient experimental infrastructure and international co-operation in sustainable networks is highlighted.

1 INTRODUCTION

Research is fundamental for any scientific or technical achievement. Safety research is one of the pillars on which the safety of nuclear facilities rests. It has to accompany nuclear installations throughout all phases of their existence, from basic design, through licensing, construction and operation, up to decommissioning. Although there is general agreement on the fundamental role of safety research, it should be worthwhile to recall from time to time the overall motivation and to review frequently the specific needs for safety research. While the need of research for future constructions is obvious, the excellent performance record of existing installations might suggest that a high safety level can be assured even with reduced research efforts. It is the objective of this paper to raise awareness of research needs for existing installations, to illustrate new trends in safety research and to point at the importance of international cooperation.

2 IMPORTANCE OF SAFETY RESEARCH

The three authors of this paper come from TSOs (Technical Safety Organisations). These organisations are the founding members of the European TSO Network (ETSON). They are clearly committed to continued safety research. The TSO concept explicitly states among the required characteristics that *“a TSO maintains an R&D programme allowing the development of new knowledge and techniques in support of its missions, and an independence of judgement from licensees”* [1]. The co-authoring TSOs have previously expressed their commitment *“to contribute further to nuclear safety through evaluation of international operational feedback, through further improvement of safety analysis methods and tools, which will certainly require a continuous effort in Research and Development”* [2].

With their conviction for the necessity of continued R&D, the TSOs are in good company in Europe and beyond. The European Energy Commissioner, Andris Piebalgs, addressing this Forum two years ago, made a clear statement about research, saying *“I believe that nuclear energy will continue to play a role in the EU, supported by a continued commitment in research and promotion of technological developments, aimed at further enhancing the safety* *and security of nuclear energy"* [3]. In line with EU energy policy, support of research activities is being continued in the 6th and 7th Framework Programme (FP). The Council decision concerning the 7th FP (Euratom) [4] states as its objective with respect to nuclear fission and radiation protection: *"Establishing a sound scientific and technical basis in order to accelerate practical developments for the safer management of long-lived radioactive waste, enhancing in particular the safety performance, resource efficiency and cost-effectiveness of nuclear energy and ensuring a robust and socially acceptable system of protection of man and the environment against the effects of ionising radiation".* The same document and later documents issued by the Commission in specifying FP7 activities in the area Reactor Systems speak about *"research to underpin the continued safe operation of all relevant types of existing reactor systems...., taking into account new challenges such as life-time extension and new advanced safety assessment methodologies..., and to assess the potential, the safety and waste-management aspects of future reactor systems..."* This means that safety research for existing installations is given equal importance as research for the development of future reactors.

Nuclear safety and regulation of nuclear activities are specific areas of activity of the OECD Nuclear Energy Agency (NEA). In 2004, the NEA issued a Collective Statement concerning nuclear safety research that expresses in a concise form the value of safety research and its potential to improve the efficiency and effectiveness of a regulatory organisation [5]. The NEA has been active to bring research and regulatory aspects together as closely related activities for maintaining and enhancing safety. There is now a common Strategic Plan for both safety related NEA Committees, the CSNI and the CNRA, both working to fulfil key objectives of the NEA Strategic Plan [6]. Insight into the role of research in a regulatory context was gained by a dedicated workshop in 2001 [7]. A follow-up workshop devoted to the same subject will be held at NEA headquarters in December 2007.

Understanding the connection between safety research and regulation is important, mainly for the TSOs and for the sponsors. In view of limited resources, it is obvious that the first priority must be the activities that support the regulator in solving pending safety issues. This is a major challenge to the researcher. It forces him to provide answers in an acceptably short time, too short for him to investigate the details that a scientist would like to understand. The answer should be helpful for the regulator, providing him a clear technical statement, although the researcher is aware of assumptions and uncertainties that cannot be readily quantified. In spite of these difficulties, it is important that research is responsive to immediate regulatory questions.

An equally important type of safety research, sometimes quoted as "anticipatory", is looking ahead to safety questions that may arise although not yet a formal safety issue. Developing calculational tools, planning experimental programmes and collecting data are research activities the regulator may profit when a pertaining safety issue comes up.

Beyond the immediate and anticipated needs of the regulator, it is important to maintain a sufficiently broad layer of basic research. This comprises the development of simulation tools, assessment methods, data banks and experimental facilities with their laboratory infrastructure. Research needs continuity to produce excellent results. To keep competence and motivation of researchers at a high level, challenging goals have to be set and maintained over a quite long time.

Although the items listed here above pertain to all nuclear installations, we restrict ourselves to nuclear power reactors for the rest of this paper.

3 MOTIVATION, TYPES OF SAFETY RESEARCH, NEW TRENDS

3.1 Driving forces for safety research

Several driving forces for safety research exist. Some of them are discussed hereafter.

First of all, operating experience feedback can contribute significantly to identify crucial needs for further research.
One example relates to the degradation of steam generator pipes, sometimes quite early in the lifetime of a nuclear power plant. Different corrosion mechanisms have been identified as contributors to this degradation. To be able to design and construct more degradation resistant steam generator pipes, research has been and continues to be essential.
Another example concerns the insights revealed by the sump clogging incident at the Barsebaeck plant in 1992. It turned out that a safety system designed for long operation in post-accident conditions might have a rather high failure probability, even in a short term. Experimentally based research showed that very complex phenomena are involved in the sump clogging issue and research efforts are to be continued up the final resolution of the problem.
Finally, operating experience feedback on fuel has also originated important research activities, including through international frameworks, e. g. the OECD Halden Reactor Project and the Phebus-FP joint experimental programme.

Fuel is also an example for safety research driven by new-technology adoption in current nuclear power plants (NPPs). Increased competition in a deregulated electricity market demands optimizing production. Responding to this challenge, advanced fuel designs with new cladding materials have been developed, fuel loading patterns have been optimised and power has been up-rated in many NPPs. These core modifications and the associated safety assessment have entailed research in several fields (cf. 3.3.2).
The adoption of digital instrumentation and control (I&C) in NPPs is one more example of a new technology that requires safety research. Very demanding reliability requirements have to be applied to the safety critical software embedded in such digital systems. This has driven important research efforts both on the side of developers and the organisations supporting the regulator.

Concerning assessment methods, there is a growing need for a better understanding and quantification of uncertainties, and this applies to deterministic as well as to probabilistic safety analysis (cf.3.2).

Sometimes it is research itself that yields findings which motivate additional investigations. A well known example is the possible recriticality of a PWR core caused by insufficient boron mixing in the course of a small break loss of coolant accident (cf. 3.3.1).
Experiments often give unexpected results or even allow disclosing hidden phenomena and variables. The thermal hydraulic integral facility PKL [8] revealed considerable differences among flows in different loops and steam generator tubes that could not be readily predicted from analyses or pre-test calculations. These results are highly relevant for the boron dilution issue.
Another example is the behaviour of iodine that was observed in Phebus-FP experiments [9]: iodine reached the containment vessel in gaseous form at a non predictable extent. The interaction of the iodine with painted walls originated an increased attention to this phenomenon.

Last but not least, an additional merit of research should not be underestimated: challenging research is an excellent means to preserve know-how and professional skills and to attract young people to the nuclear business.

3.2 Safety Margins, a cross-cutting topic for safety research

In the traditional safety analysis framework, the regulatory acceptance limits on the values of safety variables are set sufficiently high to assure conservatism with respect to the onset of damage: sufficient margins are thus enforced on these variables in the analysis of transients belonging to a complete safety case. The concept of "safety margins" accounts for the uncertainty, either aleatory or epistemic, which affects the values of safety variables. Safety margins are accordingly introduced at several stages of a decoupled analysis where successive acceptance criteria are defined with the ultimate goal of protecting the public and the environment from radiological hazards of potential releases from the plant.

A safety analysis is generally performed adopting either the deterministic or the probabilistic approach or both in combination. The deterministic approach accounts for a number of limiting transients to which conservative rules are enforced on system availability and parameter values. In contrast to this, the probabilistic approach privileges the completeness of the scenario set and the best-estimate methods. The extension of the set of design basis scenarios (the design basis space) to the almost complete set of all credible scenarios, including beyond design situations, leads to the concept of risk space.

Any change in the design and/or the operating mode of a plant may have an impact on the risk space because it could challenge safety margins in spite of fulfilling all regulatory requirements. Possible examples are power uprates, plant life extension or increased fuel burnup as well as cumulative effects of simultaneous or subsequent modifications, which can conceivably be larger than the sum of effects of each individual modification. The magnitude of the problem gets bigger as new designs push the plant closer (or even beyond) the edge of the original design space.

The framework for safety margin assessment can be easily generalized to any nuclear system described as a set of volumes constrained by successive physical barriers the integrity challenge of which can be characterized by adequate safety variables. Protective systems or features intended to preserve the integrity of these barriers or to mitigate the effects of failures, should provide the necessary level of safety assessment. The likelihood of incurring some damage in a particular event sequence can therefore be obtained from the conditional probabilities of barrier failure (or bypass) leading to damage.

3.3 New trends in safety research

In the following, we outline a few examples that illustrate new developments within traditional and new areas of safety research.

3.3.1 Circuit thermal-hydraulics

A problem in LWR safety is guaranteeing the coolability of the fuel in any normal-operation, incidental and accidental situation, including the case of a pipe rupture as a design basis accident (DBA). The development of computer codes for such challenging transients goes back to the early 70s; today, several codes are internationally available. Their physical models are based on agreed-upon assumptions on the steam and water flows and their mutual interactions. The requirements for short-term improvements are their robustness, reliability and use friendliness.

In the medium-term, it would be worth going three-dimensional, improving the two-fluid models, extending them to droplet field, and supplying a set of transport equations for the interfacial area. Meanwhile, the increasing computer efficiency should allow adopting a refined meshing and capturing small-scale phenomena, provided that more sophisticated models are available.

Computational fluid-dynamics (CFD) codes would zoom on zones of a cooling system or a containment and could be used for comprehensive analysis, thereby reducing requirements for expensive experimental programmes. Coupling between CFD and global system codes could improve the description of small-scale phenomena while keeping computer costs acceptably low.

Accidents involving fluid-dynamics as well as neutron kinetics may have important consequences, and need careful assessment both for current and future reactors [10]. For current LWRs, that is the case for the reactivity insertion subsequent to the injection of pure water in a core at shut-down for reloading. The core is under-critical in these conditions, due to the soluble boron poisoning of the water. The injection of pure water generates a reactivity initiated accident (RIA)-type transient and the core can go back critical (and, maybe, prompt-critical, depending on the amount and location of boron-free water). The power increases immediately and rises further until the Doppler feed-back is able to shut the reactor down. Then, the cooling-down can initiate a reactivity-driven oscillation. Past studies showed that such situations, due to operation mistakes, may have a non-negligible likelihood. Operating procedures have been modified to reduce the probability of such events, and suitable analyses have been performed to evaluate their consequences.

A similar problem is the boron dilution in the course of some small leaks involving a period of reflux-condensation. In this case, one of the loops delivers pure water and the other loops continue delivering water with normal boron concentration. The problem is to calculate the map of the boron concentration at the core inlet, knowing that the flow entering the vessel may be highly turbulent, and that it encounters many obstacles such as tubes and plates in the vessel bottom, before entering the core. A neutron dynamics code can then calculate the core power distribution and its evolution vs. time. Calculations of that kind are already done with CFD codes. To gain full confidence and to access fully realistic results, they need improvements in turbulence models and geometrical modelling, which implies the use of high computing power.

Other studies of accidents or operational transients use also CFD based codes to complement the usual tools and gain a more precise view of local and complex phenomena: flow stratification in pipes and tees, cold plumes touching hot walls, impinging jets with temperature differences and pressurized thermal shocks.

3.3.2 Fuel behaviour

Fuel rod failures during a transient have been, and still are, a major safety concern, in DBA such as loss-of-coolant accident (LOCA) or RIA (which could be initiated by either an uncontrolled control-rod withdrawal or a pure water injection). Such failures modify the fuel geometry thus reducing the core coolability, and eject fuel fragments to the reactor primary circuit. Detailed fuel behaviour codes already include models, correlations and properties for cladding plastic stress-strain at high temperatures, effects of annealing, behaviour of oxides and hydrides submitted to temperature ramps, phase changes, and large cladding deformations such as ballooning. They also provide fuel pellet thermal-mechanical models including fission gas. The validity of these models and their experimental data base have to be extended to include advanced fuel rod designs with new cladding materials, mixed oxide fuel, higher enrichment and higher burn-up. Moreover, the extended use of multi-scale approaches should increase the confidence in the extrapolations from experimental to reactor condition; it should also contribute optimizing the definition of the experimental programmes and to decreasing their overall cost.

3.3.3 Coupled phenomena

Safety analysis for DBAs, and, more generally, for any normal operation, incidental and accidental circumstance of the reactor life, requires neutronics, thermal-mechanical and thermal-hydraulics models. These three fields should be accounted for simultaneously because:

- the neutron cross-sections depend on the fuel temperature and the moderator density and/or void fraction,

- the fuel temperature depends on the fuel geometry, the neutronics power and the thermal exchange with the moderator fluid,
- the coolability relies on the fuel geometry.

Accordingly, incorporating full three-dimensional models in system codes enables accounting for the coupling between core behaviour and plant dynamics.

Development of several multi-physics code-systems including coupled thermal-hydraulics, fuel thermo-mechanics and neutron kinetics is underway. Among them, the NURESIM platform, currently developed in the 6th Framework R&T programme of the European Commission, and the HEMERA [11] chain, developed jointly by IRSN and CEA, the features of which are likely enabling best-estimate and penalising calculations for the safety assessment of conventional nuclear reactors, with uncertainty and sensitivity analysis.

3.3.4 Severe Accidents

At the origin of LWR design, the large break LOCA was postulated as the maximum credible accident, and the main safety design features were defined to prevent it or to limit its consequences by keeping the core geometry coolable, thus strictly reducing the release of the contaminants to the environment.

However, since the 70s and mainly after the TMI accident, it has been internationally agreed to take into account severe accidents. These are accidental situations where the core is no longer amenable to cooling. The phenomena involved in severe accidents being very complex, the main challenge for computation is the poor knowledge of the laws governing most of the phenomena involved, and, first of all, the dynamics of the large number of physical-chemical reactions.

Suitable codes, such as ASTEC [12], jointly developed by IRSN and GRS, and assessed in the SARNET framework [13], are now internationally available. They describe with simplified models, often empirically adjusted on experiments, the physical phenomena governing the reactor behaviour in space and time, from core melting up to the release of the contaminants to the environment. They are assessed on integral experiments, such as provided by Phebus FP [14] programmes.

These codes are still adopting strong approximations in the geometry description during the degradation process, and their results are largely affected by physical-chemical uncertainties, due to the large number of interacting components and the unusually high temperatures.

3.3.5 Other areas of research

The research topics that were briefly described above are examples of new trends in traditional areas of safety research. In addition to this, there are more areas where research is increasing, among them: fire, external events, human behaviour, influence of management on plant safety, etc.. The importance of some of these areas was revealed by the results of recent PSA-studies. Although these topics are not entirely new, they deserve additional research efforts.

4 INTERNATIONAL COOPERATION

International cooperation is mandatory to nuclear safety. IAEA and OECD/NEA have been working successfully for half a century now. The EC supports research cooperation through the Euratom Framework Programmes.

Since resources for nuclear safety research have become rather limited, the need for co-operation is obvious. Cost efficiency by sharing experiences, results of analyses, experimental infrastructure and data, however, is not the only motivation for co-operating. Evaluating research results together and drawing common conclusions on safety aims at a wider consensus on safety issues and ways to resolve them. While regulation remains a national competence, generally accepted research findings can promote harmonized safety evaluation practices.

4.1 Maintaining experimental infrastructure

Experiments play a major role in the development of nuclear facilities and the assessment of their safety. With respect to computer codes for the simulation of accidents, experiments have a twofold purpose: they provide information for the development of physical models and/or correlations and contribute constructing a comprehensive database for validation. Some safety experiments entail enormous costs, either due to large size, e. g. large thermal-hydraulic loops, or due to involving radioactive substances, e. g. fuel melting and fission product test installations. Nuclear tests require the maintenance of a research reactor.

While bi-lateral or multi-lateral cooperation on experimental installations has a long tradition, the systematic approach of the OECD/NEA to support member countries in maintaining safety relevant facilities and programmes deserves special mentioning. In a survey on Major Facilities and Programmes at Risk [15] completed in 2000, OECD/NEA addressed the concern that dwindling research funding would result in a consequent loss of critical competencies and reduced capability to deal efficiently with future safety problems, mainly as regards emerging safety issues. The study resulted in specific recommendations regarding the preservation of infrastructure in various safety relevant disciplines and suggested actions aimed at sustaining competencies and selected experimental facilities. Following these recommendations, several NEA projects were established based on the facilities identified in that survey as those that needed to be preserved and were in danger of being shut down. The experimental programmes performed in the framework of these projects cover relevant nuclear safety areas, notably thermal-hydraulics, severe accidents (including iodine and fission product behaviour), fuel and fire safety. In parallel, smaller projects have been started to organise operating experience in the form of structured databases, mainly in the fields of instrumentation and control systems and material aging.

After a period of five years, a follow-on study was carried out to revise the report, providing updates depending on the evolutions that have taken place in the meantime [16]. It was also recommended to think about possible uses of existing facilities, expertise and infrastructure for the development needed for advanced reactors.

Since the funding of nuclear safety research has become more stable in the last several years and because of the satisfactory performance of the above undertakings, the SFEAR recommendations address limited actions regarding the few facilities that are considered in danger. At the same time, the SFEAR recommendation to place the focus on safety issues priorities and to rank facilities vs. their capability to solve priority issues represents a relevant step as compared to the previous report. While the old report concentrated on the selection of facilities to be rescued, the recent one focuses on the remaining safety concerns and on the suitability of facilities to address them. Flexibility in addressing different technical needs is also factored in the facility ranking.

A unique piece of infrastructure for severe accident research is the Phebus reactor in Cadarache. After the completion of the latest research programme comprising five in-pile tests with fuel melting and fission product release, the future of this costly installation is at stake. In October 2004, IRSN and CEA gathered an International Experts Group (PEG) on the potential uses of the Phebus facility in nuclear safety research. The mission of the PEG was to *“identify potential programmes of integral (Phebus) tests responding to safety technical issues and likely to receive a strong scientific and sufficient financial support from the international safety community, industry, utilities and safety authorities”*.

After pondering research needs, cost, capabilities and restrictions, the majority of the PEG recommended Phebus to be maintained for future use and charged CEA and IRSN to explore several alternatives to become effective in 2015 [17].

4.2 Integrating research internationally

Exploiting experimental infrastructure by common programmes with fixed objectives over a given time period has proven to be cost effective. However, maintaining complete coverage of all safety-relevant areas by research activities requires a sustainable form of cooperation. In the long run, even the countries enjoying large safety research programmes will not be able to cover all fields alone. The best solution would be a partitioning of research work allowing each individual country to abandon specific topics and to rely on durable research efforts in another country or better in a network of countries and organisations. This requires careful coordination and reliable agreements.
An example on a bi-lateral basis is the of the source term code ASTEC [18], which allows the simulation of phenomena occurring in case of severe accidents. It is used to analyse actions that prevent or mitigate the consequences of such accidents. It is a major tool for PSA level 2 studies. Based on an agreement between IRSN and GRS, the development and validation of this code is underway and more and more organisations have already adopted it.

A major step in tackling the fragmentation that exists between the different R&D national programmes in Europe was the launching of SARNET [19]. This Network of Excellence established with support from the EC under the 6th FP is about to integrate severe accident research in a sustainable manner, notably by defining common research programmes and developing common computer tools and methodologies for safety assessment. SARNET gathers most of the actors involved in SA research in Europe. A few organizations are covering a wide range of competencies though not complete, whereas others are specialized in very specific areas and thus complementarities are developing. The critical mass of competence for performing experiments needed in the SA domain, analysing them, developing models and integrating them into ASTEC is achieved.

The most ambitious undertaking in the field of nuclear research in Europe is certainly the newly established Sustainable Nuclear Energy Technology Platform (SNE-TP). The official launching event on the 21st September 2007 in Brussels saw a large audience with high-level representatives from politics, science and economy. This Technology Platform aims at coordinating Research, Development, Demonstration and Deployment (RDD&D) in the field of nuclear fission energy. It gathers stakeholders from industry (technology suppliers, utilities and other users), research organisations including Technical Safety Organisations (TSO), universities and national representatives. It is important to note that safety research for existing installations is clearly comprised in the scope of activities of this Technology Platform.
The Vision Report [20] of the Sustainable Nuclear Energy Technology Platform was distributed at the Launch Conference. It reflects a consensus among a large group of stakeholders on the priorities of RDD&D in the field of nuclear fission, addressing the renaissance of nuclear energy with the deployment of Generation III reactors, and the development of Generation IV system, both fast neutron reactor systems with fuel multi-recycling for sustainable electricity-generating capability and (Very) High Temperature Reactors for other applications of nuclear, such as production of hydrogen or bio fuels. Important issues such as the safety of nuclear installations and the responsible management of waste are also addressed, as well as other issues which are crucial to the success of nuclear energy in the 21st century: education and training, research infrastructures, material research and numerical simulation – and funding.

5 CONCLUSIONS

There is a wide consensus that research has a leading role in maintaining the safety of existing nuclear installations over their entire lifetime. Technical Safety Organisations regard safety research as one of their essential features. They are committed to support the regulator with applicable research results, to be pro-active in initiating anticipatory research and, together with other research organisations, maintain a sufficiently broad layer of basic research in all disciplines relevant to nuclear safety.

Driving forces for safety research for existing reactors are operational experience feedback, adoption of new technologies, such as advanced fuel designs and digital I&C, more demanding assessment methods like three-dimensional and coupled calculations with quantified uncertainties, and finally outcomes from research itself in form of unexpected effects in experiments and/or results from complex analyses. Moreover, challenging research is an excellent means for preserving and updating knowledge in nuclear safety.

Research efforts are to be continued in traditional areas like thermal-hydraulics, neutron kinetics, fuel behaviour under DBA conditions and severe accidents, with emphasis on advanced methods that integrate latest experimental findings into the computational tools. The code systems should feature higher accuracy where needed, account for coupled phenomena, include supporting tools for the user and should allow for the quantification of uncertainties.

Maintaining and modernising an experimental infrastructure is necessary to solve specific safety issues of today and to provide the possibility to investigate the up-coming safety issues in the future. Experimental data are the basis for any code validation.

International cooperation is well established in form of bi-lateral and international agreements and projects. The OECD/NEA Projects have become highly efficient in addressing common safety topics by international experimental programmes, maintaining at the same time large and unique experimental facilities for future use. Transforming international cooperation in sustainable networks will enable safety research to promote nuclear safety in the future.

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