# The Vision of the European Sustainable Nuclear Energy Technological Platform Strategic Research Agenda on the Safety R&D for GEN-IV Reactors

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## 1. Forewords

The connection between safety research and regulation is fundamental in the nuclear technology. Information supplied by the research should be affordable, useful and helpful for the regulators, providing them with clear technical statements, despite the assumptions and uncertainties that sometimes cannot be easily quantified. Accordingly, safety research has to accompany nuclear installations throughout all phases of their life, from concept definition, through design, licensing, construction and operation, up to decommissioning.
Even if the excellent performance record of existing installations might suggest that a high safety level can be achieved without new huge research efforts, consciousness of research needs should be maintained, focussing on new trends, supporting public information and training.
A type of safety research, quoted as “anticipatory”, should look ahead to safety questions that may arise in the future, due to changes in the design and operating-mode, and the appearance of new concepts. Such “anticipatory” research will involve new generation simulation tools and innovative experimental programmes, to be carried out both in the main research facilities currently in operation worldwide and in new dedicated mock-ups supported by suitable laboratory infrastructures. The role of the future research should foster in an improved international cooperation to promote achieving common understanding of the safety and its standards, mainly when dealing with the advanced and revolutionary concepts which are intended to intrinsically eliminate severe accidents from occurring, and, should that not be the case, to reduce either their probability or the level of their expected consequences. This is done by design, not necessarily by addition of safety systems, which requires integrating since the beginning of the conceptual phase, the deterministic and the probabilistic approaches.

## 2. Uncertainty Analysis and “Safety Margins”: two Topics for Safety Research

A nuclear plant safety analysis is traditionally 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 parameter values and system availability; the probabilistic approach treats occurrence events in a probabilistic domain. It privileges the completeness of the scenario set and adopts the best-estimate methods.
In the traditional safety analysis, the regulatory acceptance of the limiting values of safety variables is set sufficiently high as to assure conservatism with respect to the onset of damage: margins are accordingly enforced on the safety variables. Protective and safety systems or features are intended either to preserve the integrity of the different physical barriers (three, for current reactors) or to mitigate the effects of their failures, and should provide the necessary level of “safety margins”.

The concept of “safety margins” has been traditionally used with the ultimate goal of protecting the public and the environment from radiological hazards of potential releases from the NPPs - Nuclear Power Plants -. It accounts for the uncertainty, which affects the values of the safety variables, represented as a set of volumes constrained by successive physical barriers, the integrity of which can be threatened. Protective and safety systems or features are intended either to preserve the integrity of these barriers or to mitigate the effects of their failures. Therefore, there are as many “safety margins” as barriers or systems, the loss of which can threaten the safety of the plants. Furthermore, “safety margins” exist for each damage mechanism of each barrier or system.
An extension of the concept of “safety margins” has been recently proposed, which is based on the likelihood of the conditional probabilities of barrier failure (or bypass) leading to the damage. In this approach, the set of the accidents accounted for the safety analysis (the Design Basis Accidents) is extended to the almost complete set of all credible scenarios, including out of design situations. Realistic dynamic models are adopted and the end state of a sequence is no longer based on success criteria for safety functions. Uncertainties of several types can be explicitly taken into account in the calculation of the conditional damage probabilities.
It is straightforward that the generalisation of the “safety margins” approach will show-up in an increased need for new and very demanding research, both from the theoretical viewpoint, e.g. through an implementation of the potential of the PSAs (Probabilistic Safety Analysis) and their extension to the dynamic field, to account for the response-time of devices and operators, and the experimental one, through an increased contribution of the analytical experiments to the model improvement and up-dating and some selected integral experiment for physical insight, assessment and qualification of computation tools. This will be very likely the case for the next generation of NPPs.

## 3. Challenges for Research Resources in the Evolutionary Fission Reactor Field

### *3.1 The Safety Concern*

Operating experience of current NPPs can contribute significantly to identify crucial needs for further research in the fission reactor field for advanced and evolutionary systems. Increased competition in a deregulated electricity market demands for an optimized production: responding to this requirement, advanced fuel with new cladding materials has been designed to achieve higher burn-up, new fuel materials, such as MOX - Mixed Oxide - have been introduced, more demanding loading patterns and advanced operation modes have been adopted, plant life-time has been increased and power has been up-rated in many NPPs. This trend, strongly affecting safety, will continue and amplify in the future. All the modifications adopted and the associated safety assessments are to entail research in several fields, including computer code development and extended experimental activity. Moreover, experiments contribute to the knowledge because they participate in the validation of the computer code physical models and, sometimes, they may provide unexpected results which allow disclosing hidden phenomena and ignored variables.
Advanced and revolutionary reactors encompass a variety of different designs and operating modes. They span a very large set of configurations, including small and large size cores, fast-neutron and moderated spectra, gas, water and liquid metal cooling, each one matching more or less completely and comprehensively the objectives of the GEN-IV roadmap. Natural resource optimization and waste minimization are goals more likely affordable for systems with fast neutron flux, such as SFR - Sodium fast Reactor -, GFR - Gas Fast Reactor - and LMR - Lead Fast Reactor -. On the other hand, graphite moderated, gas cooled high

temperature reactors such as the Very High Temperature Reactor (V/HTR) are more likely to be inherently safe; they also have the best potential for a diversified energy production (electricity, but also industrial heat and hydrogen).
In addition to the overall design, the core size and the operating modes and, in some cases, a strong coupling of neutron and temperature fields which can show-up in some large-size systems, the fuel, the materials for internals and vessel, the coolant features generate urgent needs which are incentive for specific research. Looking ahead, the research needs for future concepts are to be investigated, disclosed, and emphasized very early, so that the delivery of computation tools and the issuance of experimental results could match the design and safety-assessment schedules.
Designer, utilities, regulators and researchers are presently facing a very open landscape as regards the industrial maturity of concepts. Accordingly, the risk exists that the research effort outcomes will show-up either quite poor or straightforward or false.
That is actually very challenging from the safety point of view, because, even if some common features can be found among several advanced and revolutionary designs (such as operation, fuel behaviour, transients and severe accidents, their consequences, and the ways to mitigate them, as it is the case for RIA, water or air ingress), the safety assessment is strictly tied to design features, the details of which are hardly disclosed and remain widely unknown for the most concepts at the present stage of development.
In the following we analyze some specific features of the models which are most likely to be finally operated in a foreseeable future.

### *3.2 SFR*

As regards sodium technology, risk could be minimized through assessing the potential benefit of substituting conventional steam turbine energy conversion systems by gas turbine and Brayton cycle conversion and of innovative components with thermal coupling fluid (molten salt, Pb, Pb-Bi, …). The merit of innovations in the reactor design to enhance safety (including pool vs. loop type lay-out and balance of plant) is to be assessed through normal and accidental operating transient analyses in terms of robustness of the safety approach and effectiveness of arrangements made to prevent hypothetical core damage and minimise its consequences.
Special R&D efforts are to be devoted to design features enabling to practically preclude significant energy release in case of SA (Severe Accident), e.g. by advanced sub-assembly design and adoption of suitable neutron absorbers; this implies decreasing the sodium void reactivity effect and increasing the Doppler feed-back Coefficient. That should be searched for through adoption of optimised core design features such as the geometry of the fuel subassembly, the relative volume fraction of core materials, the density of heavy metal within the fuel and the possible use of light materials to moderate neutrons and increase the Doppler Coefficient. Other core desirable features for enhanced safety include reducing reactivity swing and increasing temperature margins. Furthermore, the mechanical behaviour of the core and specific design options are also to be carefully investigated so as to minimise the risk of core compaction. Innovation in core instrumentation and surveillance should allow for early detection of abnormal situations (e. g. such as local sodium boiling).

### *3.3 GFR*

As for GFR, which is a non-mature concept and does not enjoy previuos industrial experience, different safety approaches (such as those adopted for HTRs, -High Temperature Reactors- and LWRs -Light Water Reactors-) should be compared to define suitable procedures for the safety assessment. The exclusion approach should be fully discussed and validated and the

Risk Informed methodology applied all along the pre-conceptual design phase to guarantee that design is safety pertinent. Progressively, a list of Design Basis Accidents -DBA- studied should be established for margin assessment.
Several safety systems, relying on intrinsic properties of materials and system arrangements as well as on active devices, have been already studied during the exploratory phase, such as the core cooling function in tight relationship with the LPA -Loss of Pressure Accident-; the other safety functions should be analyzed in accordance to the DBA list mentioned above here. To cope with any potential danger situation, suitable passive or active systems should be implemented.

### *3.4 V/HTR*

In the case of V/HTR, additional safety challenges are raised by the coupling with conventional energy-production facilities, which may propagate instability and perturbations to the reactor, through intermediate heat exchangers. The demonstration of the feasibility of the coupling of the reactor with process heat applications and cogeneration is actually the main challenge for the short term for reactor-systems such as the V/HTR.
Industrial process heat user requirements would be quite different from utility requirements for electricity generation, and much more versatile, which will demand a high flexibility of the nuclear heat source. However competitiveness of nuclear energy is usually achieved via systematic standardisation. Competitiveness and flexibility requirements will have to be reconciled. It will require, through a conceptual design phase, the feasibility demonstration of very robust nuclear heat source that can accommodate different operational requirements and loads, a flexible coupling system matching the nuclear and industrial applications.

## 4. Some Specific Issues

### *4.1 Foreword*

Several among the above mentioned concerns can be relevant to the next generation reactor safety, but their assessment remains difficult due to the limited knowledge on the design. As a common base, the “safety by design” approach can help in thinking or re-thinking the reactor designs, even at their different stage of development, by exploiting also the adoption, since the conceptual phase and during the entire development, of the deterministic and probabilistic tools, e.g. in a risk-informed approach. Moreover and similarly, “security by design” will be centred on providing intrinsic design features, which will preserve terrorist attack or sabotage, without costly additional features.
Among the main safety-relevant issues, which can be seen as safety concerns for GEN-IV system, we mention:

- *Minimizing the risks attached to the coolant (sodium; lead, ...),*
- *Practically precluding large energy release in case of severe accident (even hypothetical),*
- *Minimizing the vulnerability to external events and aggressions,*
- *Assessing the impact of MA -Minor Actinides- bearing fuels,*
- *Diversifying the safety systems (e.g., decay heat removal),*
- *Developing an improved instrumentation for early detection of abnormal situations,*
- *Developing improved instrumentation and techniques for in service inspection and repair.*

The relevant R&D activity can be grouped in several main fields of endeavour:

- *Core Physics and Simulation*
- *Residual Heat Removal,*

- *Fuel integrity*
- *Fission product release*
- *Reduction of major risk of a broad and severe damage of the core.*
- *In Service Inspection.*

All these items claim a strong R&D effort, devoted both to code development, validation and qualification, and to measurements through ad hoc mock-up experiments. In order to achieve an optimum management of the resources, a priority scaling should be established in agreement to the envisioned technological choices.

*4.2 Core Physics and Simulation*

The requirements for core physics and operation simulation would be quite different for each GEN-IV concept-design, depending on its physical features and operating mode. Nevertheless, several trends relevant to the safety assessment can be pointed out as quasi design- independent. They would claim a major effort of computer code development, which should impulse new experimental programmes.

A sometime massive heterogeneity in space and energy and the mutual interactions between the neutron and temperature fields should claim new and enlarged 3D computation capabilities and an extended need for probabilistic techniques and coupling. Moreover, integrated systems, permitting a full description of coupled neutronics, thermal and mechanical transients, should be very worth for safety studies of strongly coupled, fast-kinetics systems, such as SFR, LMR and GFR. In contrast, for V/HTRs, due to the strong dependence of the core status on the temperatures, focus should be put on codes enabling a full coupling of the core and the reflector temperatures with the neutron field. Finally, specific needs exist for SFR and LFR, which concern the risk of a generalized and severe damage of the core, due to either reactivity-driven transients, such as the coolant void or control rod withdrawal, or mechanically-initiated transients, control rod withdrawal, or mechanically-initiated transients, such as the blockage of the coolant in a subassembly.

Accordingly, an important safety concern for GEN-IV system should be the consistency and robustness of neutronics design of those systems, the behaviour of which is quite afar from current LWRs and conventional experimental facilities, due to an allowable increased coupling among the neutron and the temperature fields (under accident conditions, also coupling to the flow field), the new design of the core, an advanced fuel technology, a very different operating mode, and an increased weight of the heterogeneities. The topic should include capabilities for uncertainty and sensitivity analysis, a relevant issue for the assessment of any new and advanced design,

*4.3 Residual Heat Removal*

For advanced and revolutionary concepts as well as many other existing ones, the verification of the sufficient cooling of the core in various accidental situations is a major task of the safety analysis. Assessment should be supported by the numerical simulation of the following processes:

- Fuel cooling by liquid natural convection,
- Fuel cooling by gas natural convection and heat radiation,
- Heat removal by active safety systems.

The difficulty will depend on design features (complexity, margin,). However, it can be assumed that existing tools, such as the CFD - Computational Fluid Dynamic - codes (including their radiation models) and the thermal-hydraulics codes already developed for current light water reactors should be sufficient. Adequate experiments should be carried-out to contribute to the enlargement of data-bases for the qualification of the codes for some specific feature of the circuits, but this activity will remain in the straight-line of current actions aimed at improving the capabilities of thermal-hydraulics codes and extending the CFD use in reactor safety analysis.

Emphasis should be put on passive systems, such as the natural convection in the loops.

### *4.4 Fuel Integrity*

As already mentioned, the integrity of reactor fuel will be a major issue for the safety assessment of GEN-IV concepts. The problems will be at least comparable to that for current NPPs both in terms of requirements and complexity. In order to enforce the demonstration of the robustness of the fuel and its resistance to the operation and accidental transients, improvements and adjustments should be made in computation tools and devoted experimental programs be developed for physical assessment and qualification. According to the fuel features and design, it is straightforward that up-dating and experiment should be reactor concept-oriented. The larger effort is foreseeable for HTR/VHTR concepts, which, despite their proven design, have accumulated a quite limited operation-experience and, far more, for GFR, the fuel design of which is new and does not benefit of any operation feed-back.

However, the simulation strategy should be significantly the same as for current NPPs: simplified models should be derived for industrial and assessed simulation tools, the development of such models should be backed by a multi-scale approach. It could be recommended to set-up a global comprehensive strategy to define the experiments against which the elementary and global assessment of models will be made.

### *4.5 Fission-Product Release*

All the phenomena involved in the transfer of fission products from the fuel elements to the primary system and further into the containment and their release to the environment are very complex. As for current NPPs, difficulty arises from the large number of physical-chemical reactions involved, which reduces the likelihood of any detailed mechanistic approach. Since the risk of severe accidents and fission product release could be significantly reduced for GEN IV concepts, it does not appear as strictly necessary increasing the present accuracy in predicting the potential consequences of severe accidents, but new actions should be initiated to adapt and assess the current computation tools to GEN IV fuels, materials and designs. That will require development of new experimental programmes including both analytical and integral tests to guarantee that all major phenomena have been accounted for.
As for current NPPs, it should be recommended to take advantage from the impending R&D activity and, whenever possible, back-up the simplified models with more detailed ones.

### *4.6 Reduction of Major Risk of a Broad and Severe Damage of the Core*

The crucial concern being the likelihood of the core melting, it is straightforward that some concepts, such as the HTR/VHTR, are more inherently protected against than others, such as the GFR, due either to a slower kinetics, a larger thermal inertia or both, and an enhanced capability, to evacuate residual power passively in almost any predictable circumstance. However, even if the designer's target is to render the core melting likelihood very low, relevant issues should include:

- Ways to prevent a local core melt-down from degenerating into a whole-core melt-down,

- Ways and means to prevent recriticalities through early fuel relocation from the core,
- The mechanism of propagation of melting subsequent to local melting (including melting itself, melt material ejection and melted core assembly-box interaction: this issue would be relevant to SFR systems),
- The consequences of a whole-core melt-down on containment integrity (including the release of radioactive elements in the environment).

Codes based on physical assumptions justifying the adoption of simplified models have been developed and are in current use for NPPs. Appropriate experimental programmes have been initiated in the 80's to assess these models. It is likely that the codes already developed for previous-generation SFR designs could be used for the preliminary assessment of GEN IV SFR, provided some complementary development and assessment works will be carried out. The adaptation of LWR codes to HTR/VHTR and GFR concepts seems possible; nevertheless since the core materials are significantly different, all should be revised and reassessed against a new and appropriate experimental data base.

### *4.7 In Service Inspection*

In Service Inspection will be relevant to the Defence in Depth of innovative concepts, such as GEN-IV reactors. The issue should be mainly addressed for liquid metal cooled reactors, such as SFRs, due to the difficulties arising from the opacity of the liquid metal, its temperature and high heat transfer coefficient, as well as the need to minimize the "drainings" of the circuits and components, to avoid oxide production. Thus, should designers favour concepts allowing easier accessibility for control, repair or equipment removal, an important R&D effort would be necessary on innovative and more efficient non destructive inspection and control devices.

## 5. **Concluding remarks**

The need for new experimental and simulation tool, aimed at sustaining safety analyses serving the needs of different stakeholders, should be focussed for GEN-IV in a definitively new perspective.

In the past, Vendors and Research Bodies have got the main responsibility for nuclear energy research activities, aimed at either achieving or complementing their own knowledge. The research activities supporting the Safety Authorities have been of far lower volume. The general public has been accustomed to get limited access to the results of nuclear safety research and has experienced difficulties in understanding the actual meaning of research results.

Today, the awareness on safety needs is completely different: the public acceptance plays a key role and may strongly affect the profitability of an investment in the nuclear field, the cost of experimental activities calls for participation of partners at the international level. All of these factors require a new approach in the perspective of the development and the deployment of a new generation of reactors, aimed at making the research results available and enjoyable to the Authorities and even to the public. Moreover, in order to be free and accessible to the Authorities and the Scientific Bodies, the simulation tools should be conceived so as to be really user friendly, to support their adoption and, as a consequence, the real dissemination of a nuclear knowledge and confidence, and of the capability of assessing the behaviour of NPPs under normal and abnormal conditions, to get a confidence on phenomena and a capability to manage nuclear technologies.

● Acknowledgments

The author is greatly indebted to the Coordinators and all the Contributors to GEN-IV and Safety chapters of the Strategic Research Agenda - SRA - of the European Sustainable Nuclear Energy Technological Platform, ESNE-TP. This paper contains excerpts to these contributions, and is widely based on the draft document elaborated by the SRA Working-Group.

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