

Summary and Main Outcomes of the NEA Nuclear Safety Research Joint Projects Week

*Success Stories and Opportunities for
Future Developments*



Summary and main outcomes of the NEA nuclear safety research joint projects week: Success stories and opportunities for future developments

For over 65 years, the Nuclear Energy Agency (NEA) has served as a flexible and powerful platform for multinational research co-operation, particularly in areas related to nuclear safety. The projects conducted under the NEA auspices have enabled nuclear safety regulators, technical support organisations (TSOs), the nuclear industry and research organisations to share research costs and results and develop expertise. This, in turn, has supported safety regulations and practices and facilitated their harmonisation around the world.

The safety research projects include experiments that address a particular safety issue and close a knowledge gap; creating and maintaining shared event, system and component databases that can be used to identify operational issues and good practices; or benchmarking safety models. They have contributed to the preservation of essential research facilities, to the development of expertise and to training and education by involving students and young professionals. With an eye to the future, special attention is also paid to ensuring the projects' data can be accessed and used in the long term.

The NEA held a Nuclear Safety Research Joint Projects Week virtual event (NEA, 2023a) from 9 to 13 January 2023 to review the accomplishments of NEA Joint Nuclear Safety Projects (NEA, 2023b) over the last four decades and to discuss future perspectives. Through a series of webinars, leaders in the sector and research project operators discussed the outcomes of close to fifty nuclear safety projects (see Figure 1) and examined how the established frameworks, research platforms and networks could effectively support future developments in nuclear energy.

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Projects have played a tremendous role to help us harmonise and have a common understanding ... of science and technology issues affecting the safe operation of nuclear facilities

... there are so many things that can be done together even in a competitive environment

William D. Magwood, IV
NEA Director-General

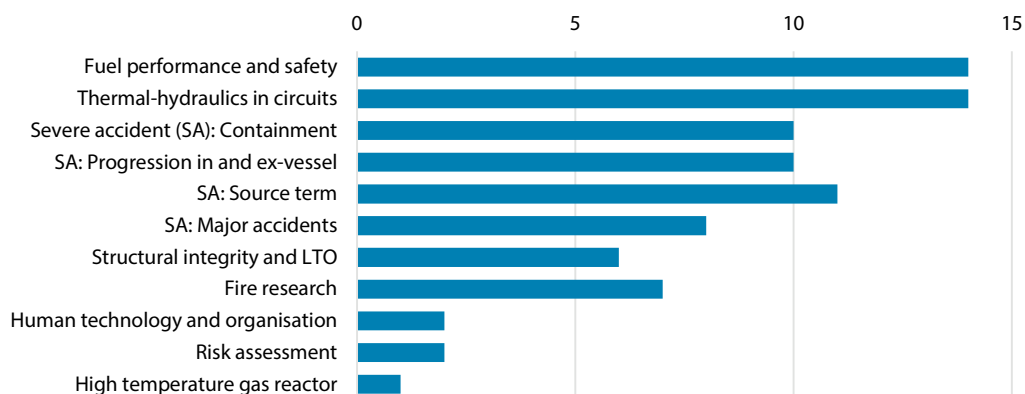


Figure 1. The safety technical areas covered by the NEA joint nuclear safety research projects

Around 450 experts from 59 countries and several international organisations attended the webinars. Participants highlighted the benefits of the NEA projects to nuclear safety stakeholders and their importance for building research platforms and the competencies needed to develop the nuclear sector.

A key point of discussion was related to the challenges ahead, in particular the effectiveness and efficiency of these activities, but also how they might better serve the development and maintenance of key skills and research infrastructures in the future.

In addition, participants explored new ways of encouraging public and private stakeholders to contribute to the funding of future safety research joint projects. Several additional objectives, listed below, were discussed and are being addressed (see also Figure 2).

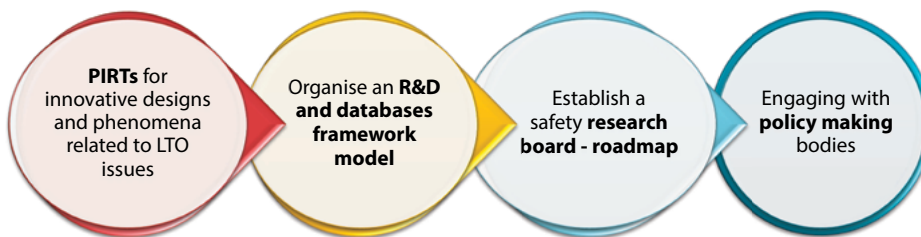


Figure 2. Proposed path forward for enhancing project frameworks and defining research plans

- Regarding the joint projects' frameworks:
 - Promoting a more integrated approach in safety research around sets of experimental platforms in the main safety technical areas, where appropriate, e.g. in the thermal-hydraulic area;
 - Engaging with policy-making bodies, efficiently recruiting stakeholders and growing the funding base;
 - Contributing more broadly to education, training and knowledge dissemination;
 - Securing the quality assurance (QA), preservation and dissemination of the project results for the benefit of the nuclear safety community and organising, where needed, database framework models;
 - Increasing interaction between joint research projects and relevant NEA working groups to broaden as much as possible the insights into the projects as well as the communities supporting them.
- Regarding research plans:
 - Establishing a safety research roadmap, prioritising work globally and by safety technical area, so as to balance the needs of currently operating and future reactors¹;
 - Developing Phenomena Identification and Ranking Tables (PIRTs) for innovative reactor designs and phenomena related to long-term operation (LTO) issues.

The following report sets out in more detail the main conclusions and recommendations of the event.

1. In this document, "future reactors" refers to Generation III, III+ and IV reactors as well as light water (LW) and non-LW small modular reactors (SMRs).

Objectives for NEA Nuclear Safety Research Joint Projects Frameworks

International co-operation in nuclear safety research is vital and participants of the Nuclear Safety Research Joint Projects Week highlighted how the NEA plays a key role and has long-standing experience in establishing fora for joint research projects, standard agreements, and best practices (e.g. in export control) as well as data preservation and distribution through the NEA Data Bank. The current frameworks proposed by the NEA are considered to be pragmatic and efficient for managing collaborative research with a range of organisations sharing interests and funding. They enable dynamic research to be managed, for example by investigating new issues and phenomena identified during a project, dealing with unexpected results, or discussing the application of results on a reactor scale. However, participants proposed several directions to improve the sustainability, efficiency and benefits of nuclear safety research joint projects.

Although only nuclear safety research joint projects were discussed at the event, some of the directions proposed may be relevant for NEA projects developed in other fields (e.g. in nuclear science, radioactive waste management and radiological protection).

To propose more integrated frameworks to better preserve and develop fundamental research capabilities and expertise in nuclear safety

While it is not the primary mission of NEA safety joint projects to help develop and maintain core nuclear safety research capabilities, experts highlighted how they have effectively contributed to this over the years (NEA, 2021). These unique experimental infrastructures, state-of-the-art instrumentation and analytical techniques remain key for the development and sustainability of the nuclear sector, for the safe long-term operation of existing nuclear plants and the licensing and deployment of future reactors. At the same time, these activities largely support the development of expertise in several nuclear safety technical areas, including nuclear fuel performance and safety, thermal-hydraulics, severe accident and containment phenomena, structural integrity and long-term operation (LTO), fire risk management and human-technology organisational (HTO) factors.

Despite periodic reviews under the auspices of the Committee on the Safety of Nuclear Installations (CSNI) to identify core nuclear safety research facilities that need to be maintained (see the 2021 update of *Nuclear Safety Research Support Facilities for Existing and Advanced Reactors* [NEA, 2021]), some core facilities have been lost or are still at risk of being lost in key nuclear safety areas, particularly in the study of potential accidental situations and the effectiveness of safety approaches and systems to deal with them.

One should bear in mind the loss of capabilities to carry out irradiation experiments (e.g. the closure of the Norwegian Halden reactor in 2018 and more recently the loss of access to the Russian MIR reactor for international collaboration) but also the planned loss of large-scale experimental capabilities for thermal-hydraulic investigations (e.g. the foreseen closure of the German PKL facility in 2024 and of the Japanese LSTF facility in the near future and the recent loss of access to the Russian PSB-VVER facility). The closure of these facilities also entails the risk of losing highly qualified expertise specific to the experimental activities in the nuclear sector.

The main risk of losing capabilities is related to financial reasons. The high costs to develop, operate and maintain, upgrade, or adapt the facilities for evolving needs² have been highlighted. This is particularly true for nuclear research reactors. Long-term commitments are needed at the international level to provide financial support for most research infrastructures in the field of nuclear safety. Establishing stronger

2. For example, state-of-the-art instrumentation to provide data to validate advanced multi-dimensional, multi-physics models, and the versatility of the facilities to address a variety of advanced designs.

collaboration in key nuclear safety areas around experimental platforms, encompassing state-of-the-art facilities in various countries with a mechanism for cost-sharing, could help develop and maintain core research capabilities. For reasons of cost-effectiveness, the complementarity of facilities from different organisations should also be considered to a greater extent than in the past. Indeed, to address different technologies, design boundary conditions and scales, it would be beneficial to collaborate around sets of multi-purpose facilities able to address new questions and covering a wider range of interests.

For example, experimental reactors providing for transient irradiation testing capabilities have been considered essential to support nuclear fuel design, validation and performance. This is why the NEA Second Framework for Irradiation Experiment (FIDES-II) (NEA, 2023c) and related Joint ExpERimental Programmes (JEEPS) have been launched with the support of a large community. This framework is considered an essential and effective step in maintaining irradiation capabilities. However, continued attention should be given to smaller and unique facilities at risk which provide for out-of-pile testing.

In the same vein, it is recommended that the development of similar research frameworks in other key nuclear safety technical areas be considered. The objective would be to define sets of complementary experimental facilities with mechanisms to maintain and develop capabilities to address a wide range of interests, to develop and extend a strong partnership, to support facilities' operating agents and to maximise the value of acquired knowledge. In addition, consolidating co-operation between various facilities and experimenters contributes to the development of solid technical expertise.

Thermal-hydraulics is considered a priority technical field. A number of core facilities will be closed in the near future. New facilities dedicated to future reactors and related safety systems, including passive safety systems, may become available for collaborative research in the coming years and several safety issues both for operating and future reactors are already identified and need to be addressed. Other options need to be explored to address questions related to structural integrity and long-term operation (LTO), in particular how to establish co-operation on "harvesting activities" and related research, as well as new issues related to severe accident and containment phenomena.

A first step could be to organise fora of critical facility owners in key technical areas. This would identify the core facilities that will be open to collaborative research in the short and long term, as well as the safety topics that can be addressed in these facilities. International joint projects could thus be judiciously organised in conjunction and complementarity with national projects to provide additional support for operating agents.

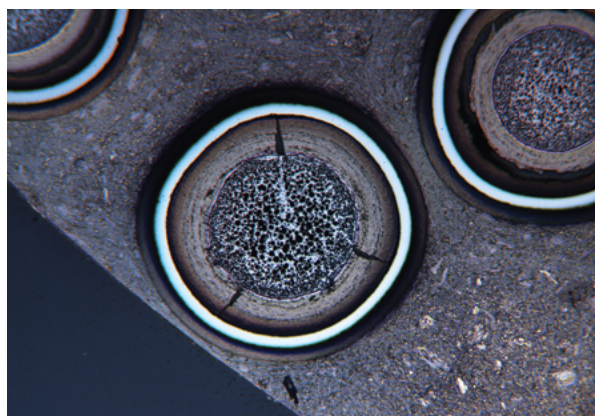
TREAT reactor.

Idaho National Laboratory, United States



Individual TRISO fuel particles at 100 µm scale.

Idaho National Laboratory (CC BY 2.0)



To involve more stakeholders to broaden the projects' partnership and funding base

Different stakeholders in the nuclear sector with various responsibilities and interests (regulators, technical support organisations [TSOs], research institutions and laboratories, industry including both utilities and vendors), have joined NEA nuclear safety joint research projects over the years. The experience shows that it is essential to have all stakeholders involved at a very early stage in defining a project if they are to derive maximum benefit from it. In addition, preparatory discussions are essential to convince a wide range of potential partners to become involved in the project to increase its added value. Mechanisms should be set to have appropriate upstream discussions to get stakeholders on board in due time.

The number and type of members in a project will affect its robustness and sustainability. Having more members makes it possible to share the costs and risks of the project, facilitating the performance of experiments. There are several advantages to recruiting new members: increasing the budget or reducing the cost burden on members and the participation of a larger set of experts, mixing different skills and adding insight into experiment design and analysis, ultimately increasing the value of the experiments. Strengthening the networking opportunities is a good way to attract more organisations to projects. Fora, open seminars valorising the safety applications of project results, and co-operation frameworks with external scientific communities in areas not specific to the nuclear sector (e.g. human-technology organisation [HTO], fire risks, cybersecurity, external events, application of digital technologies and artificial intelligence [AI]) could help motivate new parties. In addition, establishing common understanding between different stakeholders should ultimately facilitate discussions related to licensing between independent stakeholders.

It is also essential to broaden the funding bases if there is a need to cover a wider range of interests. Some governmental organisations currently fund most of the NEA's joint research projects on nuclear safety and these organisations have expressed concern that they will not be able to participate in additional projects requiring more funding than they are currently investing.

Recruiting more industry partners to share the funding allocated to a country could broaden the funding base for projects. For example, projects addressing issues that would facilitate the licensing process could be of great interest to industry and utilities. At the same time, as the industrial landscape in the nuclear sector evolves, including with newcomers and smaller companies, it may be interesting but challenging to find adequate mechanisms to attract these newcomers. Setting up the appropriate frameworks and agreements to conduct collaborative research in the best interest of all stakeholders will require particular attention to issues such as balanced discussions with all stakeholders, conflicts of interest and the challenges of disclosing scientific data. It would be interesting to plan more information meetings to make industry decision makers and the research laboratories that support industry aware of any proposed joint projects and to assess how these could be designed to also meet some of the priority research needs not covered from the industry sector perspective. This initiative can be discussed under the auspices of the CSNI.

Recruiting partners from nuclear countries currently not involved or with low involvement in joint projects is another way of broadening the funding bases. Efforts could be undertaken to make these countries aware of the opportunities offered by the current framework of joint projects. Furthermore, mechanisms could be put in place to facilitate access for "new" nuclear countries to support capabilities building in these countries. In some cases, export control issues may limit the possibilities of adding new members to some projects. These limitations should be addressed during upstream discussions related to project development.

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NEA projects allow EPRI to leverage our members' research dollars, connect to a global network of peers, and accelerate deployment of technology

Jean Smith
EPRI

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For newcomers countries in the nuclear field, the co-operation and the partnership is very important to have sustainable safe nuclear programme

Raoul Awad
FANR

To make a wider contribution to education, training and dissemination of knowledge

In general, knowledge, data and expertise gathered through nuclear safety joint projects enrich the body of scientific knowledge underpinning nuclear safety. Joint projects contribute to nuclear safety capability building in the participating countries. Conversely, the communities involved in the projects have a responsibility to share the knowledge gained more widely for the benefit of the nuclear safety community as a whole. Projects should help to create a safety culture and expertise in nuclear developing countries and to maintain or strengthen it in nuclear countries, where necessary.

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A major challenge is to attract young students in the nuclear sector; research done in the joint projects is international top level research with a lot of potentials to attract young talents

Katharina Stummeyer
GRS

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Halden secondees have become technical experts in member countries

Toyoshi Fuketa
NRA

The projects generally involve the active participation of young scientists (PhDs, post-docs.) in experimental and analytical activities, mainly from participating organisations with research activities. Often, students from universities collaborating with participating organisations have also been involved in joint project activities.

While the interest of young researchers in the nuclear sector declined after the Fukushima Daiichi Nuclear Power Plant accident, the trend seems to be reversing, with increased interest linked to the development of new technologies such as SMRs.

Including strong co-operation with major universities in a project is of great value. Universities and research laboratories have made and continue to make very valuable contributions to some projects, providing access to complementary smaller-scale testing capabilities and resources devoted to the development and validation of fundamental models. These added capabilities benefit the project communities overall. Project members should be encouraged to consider academic institutions' involvement in the design, development and execution of joint projects.

Conversely, a joint project can be an opportunity to develop educational tasks, as was done e.g. in FIDES-II, HALDEN, HYMERES, TAF-ID and TCOFF. Training and education should be offered to project members and, where appropriate, non-members. This can be done, for example, by organising summer schools or seconding trainees

to facilities. The current framework allows for personal secondments to facilities, which in the past was e.g. efficiently used at Halden, with secondees who became recognised fuel safety experts and it would be valuable to make greater use of this possibility to supervise and train new experts in nuclear safety.

In the future, it would be beneficial to dedicate in all new safety research projects resources and a part of project budgets to support training and education tasks.

A partnership with the NEA Nuclear Education, Skills and Technology (NEST) framework (NEA, 2023d) could also be envisaged, as it has been implemented, for example, for the HYMERES safety project.

Systematic sharing of project outcomes contributes to the dissemination of “safety knowledge”. Project communities should consider organising extended workshops (involving non-members or other related communities) during the project. The participation in major conferences (with, for example, dedicated project sessions) in key safety technical areas should be considered more systematically. Past positive experiences in this respect should be used to implement, as far as possible, such dissemination activities in all ongoing and future projects.

To preserve and disseminate high quality data produced by the joint projects

Most projects, after a period of non-disclosure, deliver data packages to the NEA Data Bank (NEA, 2023e) for preservation and distribution to NEA members on request. The NEA Data Bank has extensive experience in the preservation and dissemination of data. The crucial role of the NEA Data Bank as a central, secure, and durable repository for key datasets relevant to nuclear safety applications is well recognised.

Having a common database for safety applications, with legacy data sharable and available, brings great value to the safety community and is seen as cost-effective.

Ensuring a high level of quality for the data used to develop and validate physical models of safety codes is essential for risk assessment (through probabilistic safety analyses [PSA] and reliability analyses) and the evaluation of safety margins. Having high quality data as part of the joint project helps to build confidence in safety assessments. Durably preserving data and providing users with reliable information on their quality insurance (QA) is considered essential.

The NEA and the project communities have a common interest in guaranteeing the quality and completeness of the data made available to member countries. These data should include as much as possible raw and processed data, as well as explanatory documents (e.g. technical reports) in order to be usable. They can thus be used over the long term in a safe and sustainable manner. Though there may be proprietary or export control issues in some cases, data collection should prevail in all cases, with appropriate distribution schemes and distribution agreements in place with data owners. The NEA has for instance engaged substantial efforts to collect the Halden project (NEA, 2023b) legacy database, which is a unique resource compiling the results of 65 years of research on fuel performance and safety, and to propose appropriate distribution schemes.

Processing key data sets, as part of more collaborative activities such as International Standard Problems (ISPs) and benchmarks, is an efficient tool for assessing data completeness and QA for safety applications, although such activities generally require significant resources. Selected data sets from most, perhaps all, projects have been processed through ISPs or benchmarks, including blind and open phases, with generally documented results. Some projects, such as RBHT (NEA, 2021), have been specifically designed for benchmarking codes with co-ordinated blind and open benchmarks for all generated data sets and detailed uncertainties evaluations for a selection of data sets. More systematic approaches to exercise data should be implemented in all projects with collective engagement of project members. This way, members get better value from projects with qualified data and enhanced codes.

In addition, it is important to have appropriate tools to easily search and find data in large databases (e.g. for comparative analyses of test series or counterpart tests). Current databases do not necessarily provide appropriate search tools. It could be useful, in that respect, to assess the cost-benefit ratio of modern technologies such as artificial intelligence. The NEA Data Bank could assess the potential benefits of using modern tools to query large databases.

Nevertheless, managing and keeping alive large databases (making them updated, with information on data QA, and durable) requires significant manpower and is costly. This is why the NEA identified two

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Data preservation in (an) efficient and easy-to-use manner is a very urgent issue because many experts are retiring. A qualified documentation of the data is as important as data production

Ki-Yong Choi
KAERI

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The preservation of key facilities, skills, high-quality data is essential (for the nuclear industry)

Manuel Carrasco
EDF

major actions: 1) to summarise best practices in data preservation and dissemination and recommend enhancements; and 2) to prioritise the effort on databases which will undoubtedly be used extensively in the future. The Senior Expert Group on Preservation of Key Experimental data sets, which operates under the CSNI, in relation with the Nuclear Science Committee (NSC) and the Management Board for the Development, Application and Validation of Nuclear Data and Codes (MBDAV), will provide conclusions and recommendations on efforts needed and best practices in 2024.

In parallel, a number of activities have been proposed to specify the priority data needs in the nuclear fuel and the thermal-hydraulic fields³ and for databases supporting LTO, such as material ageing databases. The nuclear fuel and the thermal-hydraulic database will be used to assess the safety of future light water reactors (LWRs) with use of current and near-term new fuels and claddings⁴, and will be possibly extended, or specific databases created, to address non-LWR technologies and advanced fuels⁴. Following these specification activities, building the databases themselves will require substantial expert manpower and funds which could be appropriately set through joint projects. A broad commitment from nuclear stakeholders to support future joint projects on safety databases for nuclear fuel, thermal-hydraulics and LTO would benefit the nuclear sector and be cost-effective.

To benefit from closer co-operation between joint projects and relevant NEA CSNI working groups as well as between the joint projects themselves

Increased networking is a good way of advertising projects and ensuring that their development is supported by the widest possible community.

It is useful to put in place mechanisms to allow experts from CSNI working groups in given technical areas to contribute with as many points of view as possible when developing projects and evaluating project results. Such mechanisms are already in place in some CSNI working groups and appear to have been efficient. They comprise:

- Systematic presentations of joint project proposals by operating agents in working group meetings and collection of insights from experts;
- Systematic presentations of projects outcomes with focus on applications by operating agents;
- The organisation, with the approval of projects members, of analytical activities (e.g. International Standard Problems [ISPs], benchmarks) accessible to non-members to further assess key project data sets.

Other meetings, such as expert groups to review the scope of project proposals or final project workshops with wider participation (beyond members) usually jointly organised by the NEA and the operating agents, should be systematically advertised in the relevant working groups under relevant standing technical committees, in particular the CSNI.

Working groups' "strategic" documents (see for instance NEA [2023f], recently released by the Working Group on Analysis and Management of Accidents, or WGAMA) as well as state-of-the-art reports, ISPs, benchmarks and workshop conclusions can effectively inspire the development of project proposals, as they generally highlight research gaps. An example is e.g. reports released by the Working Group on Fuel Safety which highlighted research gaps in Reactivity Initiated Accidents (RIA) which are addressed

3. In these two areas, the NEA has launched activities to work on specifications for databases, under the Working Group on Fuel Safety and FIDES-II for fuel safety and under the Working Group on Analysis and Management of Accidents for thermal-hydraulics, starting from the past CSNI Code Validation Matrix effort (NEA, 2014).

4. The same definition is used here as in Table 1 of the FIDES-II strategic plan document (NEA, 2023c).

in the ongoing CABRI International Project (CIP) and FIDES-II HERA (NEA, 2022). Other documents, such as working group discussions and country reports in working groups can also be the source of project opportunities. It may be recommended for working group members to invite project operating agents to participate in working groups meetings and activities and to share the findings and recommendations of these activities more widely in their country.

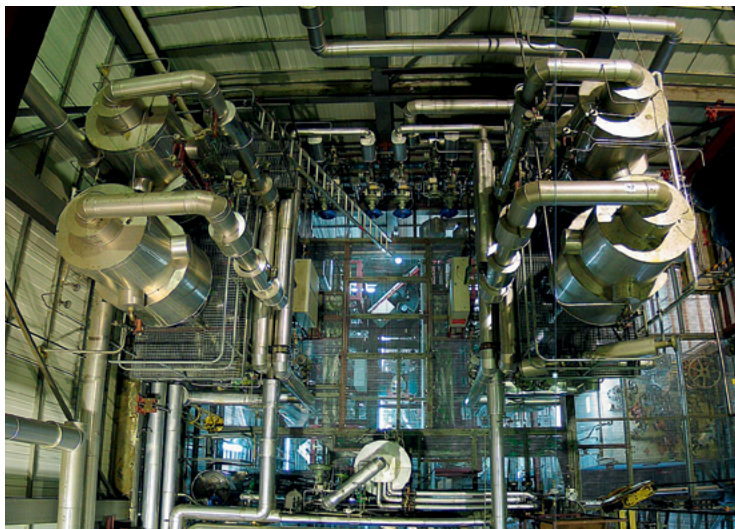
The CSNI Programme Review Group (PRG) and the CSNI are informed of project proposals and project summary reports at an early stage. CSNI members are advised to make their organisations and networks aware of project proposals.

Co-operation between relevant projects could be enhanced by organising counterpart testing, joint workshop or joint benchmark activity. This has already been the case in the past, for example between thermal-hydraulics projects (ROSA, PKL, ATLAS) with counterpart tests, joint benchmarks and analytical workshops or fire projects (PRISME, FIRE) with common benchmarks. It could be applied in other technical areas, such as between HALDEN, SCIP and FIDES-II regarding loss-of-coolant accidents (LOCA), between PANDA and THEMIS regarding containment and safety systems issues, or between ESTER and THEMIS regarding source term issues. See (NEA, 2023b) for information on above-listed nuclear safety joint projects.

View of the ATLAS experimental loop.
KAERI, Korea



Top view of the PKL facility.
Framatome, Germany



Research perspectives

Establish priorities and provide guidance for the development of convincing project proposals for decision makers

Several new reactor and fuel concepts are currently being considered for deployment, and the ability of regulators and TSOs to respond in a timely manner remains a challenge. An increasingly wide range of concepts (for example, reactor designs including Generation III+ and IV, SMRs with LWR and non-LWR technologies and, possibly, non-electric applications, near-term new fuels and claddings and advanced ones⁴, advanced materials, and passive safety systems) could have an impact on safety assessment methods. At the same time, questions remain concerning large LWRs in operation, in particular to ensure long-term sustainable operation beyond 60 years and modernisation⁵.

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Nuclear safety research should look ahead and help us being ready for the future with licence renewal for existing reactors and new reactors applications (light water, non-light waters, SMRs)

Ray Furstenau
US NRC

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The NEA could play a key role in setting up the international safety research agenda and define priorities for research projects

Jean-Christophs Niel
IRSN

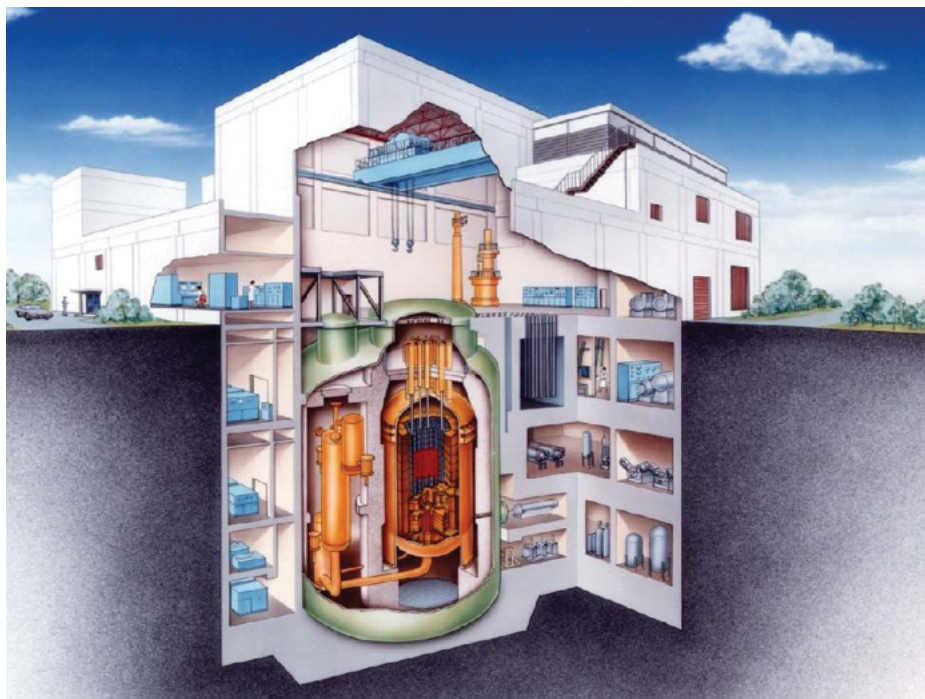
It is necessary to prioritise and concentrate efforts on the main nuclear safety issues for technologies whose deployment is envisioned in the short term and for those that must be maintained in operation. The challenge could be to find the best funding balance to support these two types of needs and associated core research infrastructures.

With the support of the CSNI, creating a comprehensive high-level roadmap for prioritising nuclear safety research needs and identifying major gaps and capabilities requirements would help research facility operators develop appropriate joint project proposals. The roadmap should determine whether current and planned research capabilities are sufficient to meet regulators' needs in their independent safety assessment.

This roadmap must use input from previous NEA initiatives. The NEA is developing *The NEA Small Modular Reactor Dashboard* (NEA, 2023g) to characterise nuclear technology development and economic perspectives. It has also put in place, under the CSNI, the Expert Group on Small Modular Reactors (EGSMR), which has recently provided the CSNI with research recommendations to support the safe development of SMRs (NEA, 2023h). One of the challenges is that the research is currently focused on deployment and technology needs rather than identifying the R&D issues that should be addressed to build confidence in the robustness of these technologies with respect to safety goals and requirements, for instance investigations related to demonstrating the effectiveness of the management of potential accidents in new concepts.

The other challenge is that there is currently a lack of design-specific data in the public domain to support the safety assessment of reactor designs under development, such as SMRs. There is a need to establish a consensus on which generic phenomena should be given priority.

5. For instance, accident tolerance of high power reactors, management of severe accident with core melt, limiting further radiological consequences for potential accidents, use of new technologies like digital I&C, cybersecurity, artificial intelligence.



High-temperature
Engineering Test
Reactor (HTTR).
Japan Atomic Energy
Agency (JAEA)

Moreover, a number of research facilities that have been developed to support the design of future reactors, including SMRs, are not open to collaborative research. An IAEA-NEA joint effort has been launched under the Nuclear Harmonization and Standardization Initiative (or NHSI, an IAEA complementary initiative that aims to advance the harmonisation and standardisation of SMR design, construction, and regulatory and industrial approaches) to create by mid-2024 a booklet listing the facilities available for collaborative research. More generally, synergies between the NEA, IAEA and European Commission joint research projects could also be beneficial in some areas.

Based on this roadmap, the CSNI should assess the need to extend the expertise of its groups to technologies other than LWRs and to advanced fuels and claddings, and to advanced materials⁶. In the short term, it is important to achieve a timely rebalancing of R&D programmes, which currently focus mostly on large LWRs and conventional fuels and claddings. This could be achieved by organising Phenomena Identification and Ranking Table (PIRT) exercises to identify major gaps and pressing issues. Such exercises would certainly help to define project proposals to meet these priority needs.

CSNI working groups could also consider assessing the potential applicability of existing knowledge and data to different technologies, for instance to LWR SMRs; some may be applicable, others not. It would also be useful to identify data to support code verification and validation (V&V) for SMR safety assessment applications.

The next paragraphs summarise points of discussion developed during the joint projects week regarding research perspectives in different safety technical areas.

6. For instance, SiC cladding, TRISO-SiC composite pellets and high density fuels.

Perspectives in fuel safety research

Advanced fuel and reactor developments represent good opportunities for the nuclear sector but also challenges to address all possible envisioned options. Needs for fuel safety research are expanding with plans to soon deploy near-term new fuels and claddings and, in the medium term, advanced fuels and claddings (NEA, 2023c). To progress in the Technology and Licensing Readiness Levels (TRLs and LRLs) of new fuels and claddings, different testing steps are usually conducted before full-scale assemblies are used in the commercial operation of nuclear power plants, starting with the determination of fundamental properties, out-of-pile testing, in-pile testing in representative operating conditions (in material test reactors [MTRs] or at limited scale in commercial reactors), in-pile testing in transient and/or off-normal conditions (in MTRs), and testing in commercial reactors in real operating conditions (lead test rods or test assemblies). The relation between the concept of TRLs and the testing stages has been discussed in (NEA, 2023c).

At the event, it was said that FIDES-II provides the right approach to supporting MTR testing but is facing a number of challenges. The main challenge is that currently available testing capacities are not at the level of those offered in the past, with the recent closure or unavailability of a number of MTRs (such as Halden and MIR). Capacities in operating MTRs (such as TREAT at INL, BR2 in Belgium, LVR-15 in Czechia, and NSRR in Japan) are limited in comparison, for example, to what Halden was offering, or in some cases have yet to be established for representative testing. As the capacities are limited, there is a much greater need to plan and design the most valuable tests. Co-operation upfront with all stakeholders is important, even more so when it comes to designing experiments with limited capacities. Further, the few MTRs that are operational are old. It was said that the CSNI WGFS and FIDES-II should identify long-term research needs and the next generation of MTRs, as in-pile transient testing is essential for safety assessment and licensing process.

Establishing research priorities in the fuel safety area is all the more important with expanding needs and limited in-pile testing capacities.

Unless there is strong co-operation between all stakeholders, including vendors and utilities, to support the development of additional capacities, using at best complementarities between MTRs, commercial reactors and, where relevant, out-of-pile testing, prototypic testing might not be achievable in due time to demonstrate the safety of all envisioned near-term and advanced fuels and claddings. One additional challenge is that not all nuclear countries are pushing to investigate near-term new fuels and advanced fuels. Some countries have expressed the need to design long-term collaborative research (for instance for TRISO fuel) as there would be more possibilities to collaborate with fuel developers upfront, as long as TRLs are low or intermediate. It may become more challenging when TRLs are high as, when vendors come close to sell their materials, it becomes more challenging to exchange data due to proprietary rights.

The development of joint projects around MTRs (named JEEPS in FIDES-II) needs an operator to maintain and operate the MTR, industry to provide fuel irradiated in commercial reactors, organisations to support projects and end-users to identify open safety issues and valorise the project results. The community would clearly benefit from vendors and utilities co-operating to provide irradiated material with several years of irradiation for transient testing and the related data and information. This is clearly a challenge for advanced fuel to be used in non-LWR reactors as there are currently no commercial reactors to provide long-term base irradiation under prototypic conditions.

It would be beneficial to have more vendors and utilities contributing to collaborative research, e.g. participating in FIDES-II, and providing material of interest for testing. Identifying material that can be made available for testing and creating a schedule for such testing could help establish priorities.

Regarding LOCA testing, it could be beneficial to review and use at best complementarities between in-pile testing (for instance Halden, testing planned in FIDES-II) and out-of-pile testing (for instance hot cell LOCA

tests at Studsvik done as part of the SCIP project). Further collaboration between HALDEN, FIDES-II and SCIP projects on LOCA with, for example, “counterpart” testing and/or common benchmarking exercises would be beneficial to prioritise needed testing.

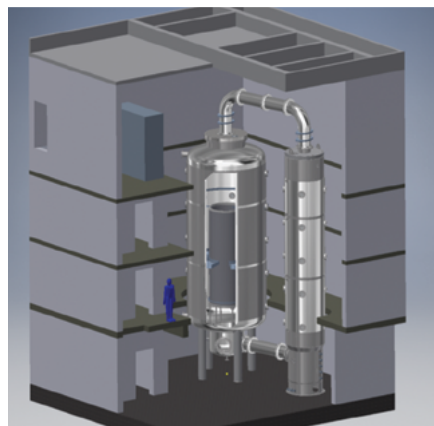
Perspectives in safety thermal-hydraulic research

As highlighted above, with the planned closure of a number of facilities that were involved in joint projects, thermal-hydraulics is an area where the development of frameworks around sets of complementary experimental facilities is seen as a proper way to address needs for both operating and future reactors. This would consolidate collaborations and synergies between facility operators and related joint project communities in the area. Actions would need to be launched to discuss how to establish such frameworks. This was discussed at the joint ATLAS-3/ETHARINUS analytical workshop held in November 2023 in Barcelona with potentials for establishing more integrated approaches around reactor coolant system and containment facilities. The organisation of joint analytical workshops or benchmarks could also be envisaged for containment research facilities around, for example, the German THAI+ and Swiss PANDA facilities.

The NEA could also foster discussions with operating agents or organise operating agents’ fora to identify the core facilities that will be open for collaborative research in the near and longer term and the safety issues that may be addressed in these facilities both for operating and future reactors. These reviews would involve operating agents with facilities that are already involved in collaborative research, but also operating agents with facilities that are planned to be open for collaboration in the near future.



The PANDA reactor pressure vessel.
Paul Scherrer Institute,
Switzerland



Scheme of the THAI+ facility.
Becker Technologies,
Germany

There is also a need to agree on which generic phenomena to address as a priority. It has been recommended to organise PIRTs in WGAMA related to LWR SMRs and eventually non-LWR reactors, including SMRs. Phenomena such as heat removal in large water bodies by natural convection are of specific interest to address the efficiency of passive heat removal systems, which are more widely considered in future LWR reactors, including SMRs. The thermal-hydraulics of passive safety systems warrants further research to reach consensus on the efficiency and reliability of such systems. Modelling such systems is a challenge for thermal-hydraulic codes and the systems used in SMRs are not planned to function with the same boundary conditions as for large LWRs.

Scaling still needs to be addressed, in particular for SMR applications. Although methodologies to address scaling issues have been established, counterpart testing in complementary facilities at different scales is irreplaceable to validate scaling approaches. Developing frameworks around sets of complementary experimental facilities, as proposed, also offers opportunities to validate the scaling of models for small and large reactor applications.

There is a need to assess how the extended thermal-hydraulic database established for large LWRs is applicable to SMRs, with no operation experience in the public domain to rely on for SMRs. The NEA, and in particular the WGAMA, have taken action to review the current status of thermal-hydraulic databases, based on experience of the containment code validation matrix CCVM (NEA, 2014). The WGAMA is leading an activity for the harmonisation of methodologies for system thermal-hydraulics' experimental metadata preservation (called THEMpo), which is a precursor to developing a thermal-hydraulics database that will be used in the future for both operating and future LWR reactors. As such a development will require large resources and will be more efficiently addressed through collaboration, it has been suggested to address the effort in the future as a joint project with shared funding. All stakeholders in the nuclear sector should see an interest in contributing to this effort as it would support the licensing of future LWR reactors.

Perspectives in severe accident research

There are still immense challenges ahead related to the Fukushima Daiichi accident. International collaboration should continue, first through the ongoing FACE project (NEA, 2023b) to inform decommissioning and to make better use of the insights from the accident analyses for severe accident management for operating and future reactors. With respect to that, a workshop on future research to enhance accident management in operating and future reactors informed by Fukushima Daiichi insights is planned for the end of September 2024. The workshop objectives are to get regulator and industry views on the application of the Fukushima Daiichi accident insights to accident management and to evaluate the remaining research needs in the area. Technical sessions are planned with potential operating agents of future projects offering research capabilities for further enhancements of accident management in operating and new reactors. The aim is to establish recommendations on future directions for collaborative research in the area, including recommendations on needed capabilities, and to help maintain core research facilities at risk and develop new ones, as necessary, after the completion in 2024 and 2025 of seven NEA projects (ATLAS-3, ETHARINUS, QUENCH-ATF, THEMIS, ESTER, PANDA, ROSAU) related to investigations of Fukushima Daiichi issues.

Regarding severe accidents extending to core melt, modelling all phenomena in detail is known to be very challenging. Related research involves unique facilities and a long-term built expertise, for instance for prototypical corium, hydrogen combustion and chemistry studies of fission products (related to source term) and is costly. There is a need to focus the research in this area, considering the remaining major gaps from the viewpoints of industry, regulators and researchers. It was said that it is important to continue working on the demonstration of the efficiency and reliability of accident mitigation systems in prototypic geometries and boundary conditions both for operating and future

reactors. Investigations performed for large LWRs and related accident scenarios are not necessarily applicable to LWR SMRs. The demonstration of the efficiency of approaches and systems to prevent or mitigate severe accidents in future reactors, including SMRs, needs to be supported on technical grounds. A stronger involvement of reactor vendors and utilities in research supporting the demonstration of the validity of severe accident management approaches for new designs would certainly increase confidence in their deployment.

There are some pending issues related to the accident tolerance of near-term new fuels and claddings, including so-called accident-tolerant materials, and of more advanced fuels. Research in this area should continue beyond the current QUENCH-ATF project, which addresses accident-tolerant claddings.

There is a need to preserve beyond 2024 capabilities developed for corium and source term investigations, e.g. through the ROSAU, THEMIS and ESTER projects, to alleviate uncertainties related to the ability to cool and isolate degraded fuel-containing material and keep radioactive releases to the environment under appropriate limits. This is key for demonstrating that accident management measures and emergency planning are appropriate for future reactors, including for SMRs. However, it is also required to design an effective approach to prioritise the needs for future reactors, possibly through dedicated PIRTS and associated validation matrices, and to get more support from industry.

Finally, it was suggested that new activities be considered to assess the benefits of using AI and machine learning (ML) techniques to increase the effectiveness of accident analyses.



Test facility for ROSAU corium melts spreading tests.
Argonne National Laboratory (ANL), United States



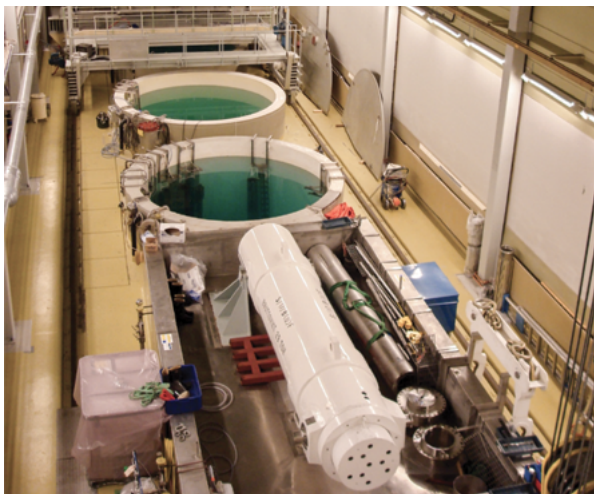
CHIP experimental facility to study fission product transport and deposition in the primary circuit.
IRSN, France

Perspectives in LTO research

Ageing related to the irradiation of structural materials is planned to be investigated in the near future in the FIDES-II framework in MTRs. The strategic objectives in this area are described in NEA (2023c). The FIDES-II INCREASE JEEP has recently been launched to establish capabilities in the area. Research needs for structural material ageing under irradiation are listed in NEA (2023c). There is clearly a need to prioritise safety research needs related to LTO beyond 60 to 80 years, which is now planned in a number of countries for operating nuclear power plants. Further, operation beyond 80 to 100 years is envisioned for future reactors and research to establish such potentials should as well be designed. An activity has recently been launched under the CSNI Working Group on Integrity and Ageing of Components and Structures (WGIAGE) to identify major gaps and research needs related to LTO beyond 60 years. This activity will provide directions for collaborative research.

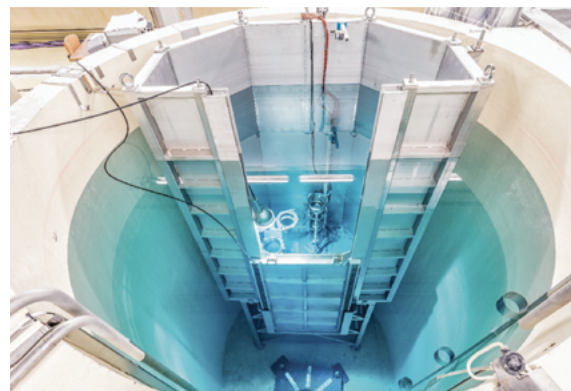
As a number of nuclear power plants have recently been shut down worldwide (retirement after long-term operation or closure) and are being decommissioned, unique opportunities exist for harvesting material aged under actual operating conditions, including material with long operation histories of up to 30 years of full operation. Harvesting material in plants is valuable with respect to providing prototypical materials (when compared to material artificially aged in laboratories) that can be used to develop ageing management strategies to support extended reactor operation periods of 60 years and more. However, harvesting is a costly proposition that requires the strong involvement and close co-operation of all stakeholders (regulators, researchers, utilities and companies in charge of plant decommissioning).

The NEA SMILE joint project (NEA, 2023b) conducted by Studsvik in Sweden provides a first-of-a-kind large collaborative effort around aged metal material harvested in Swedish plants being decommissioned. In Sweden, all stakeholders involved in plant decommissioning, in the harvesting of aged material and in research on harvested material work jointly for the success of the research project, with the support of organisations from other countries. Such a project offers a unique opportunity for stakeholders in a number of countries to discuss aspects such as the challenges related to harvesting material on-site, performing on-site measurements, collecting historical information and data on harvested material, calculating environmental loads on materials during their in-service life, and collecting and preparing the most prototypic samples for further characterisation and testing. It is also a unique opportunity to share experience and good practices and optimise characterisation and testing methods.



Studsvik pool facility for storage and inspection of SMILE materials.

Studsvik, Sweden



The safety community would benefit from a more integrated approach to collaborative research on material harvested in plants in the future, extending beyond the current scope of SMILE, considering material of interest harvested worldwide and materials other than metal (for instance concrete and electrical cables) for the interest of a wider range of countries/organisations. SMILE's access to a number of reactors at various stages of decommissioning and dismantling already provides for a large stream of samples and test results from various source materials that are applicable to BWRs, PWRs or VVERs but other sources of material would be beneficial to extend the knowledge base.

Conducting an exercise to compile in a library which material is currently available for collaborative research would be of interest for the development of future joint projects proposals. The library would include materials that can be offered for international research, with good historical records and matching priority needs for LTO.

At the same time, the prioritisation of research needs that have been initiated for metal components through the US NRC-NEA International Harvesting Workshops held in 2020 and in 2022, and the identification of target material to address priority needs, should continue with a broader participation of interested stakeholders.

Nuclear regulators could more clearly endorse harvesting as an important, technically-robust approach to materials' characterisation for long-term operation and consider how to engage more utilities in harvesting activities for the benefit of long-term operation and nuclear safety. Relevant standing NEA committees, the Committee on Nuclear Regulatory Activities (CNRA) and the CSNI could engage further to promote harvesting research activities. At this stage, there is no regulatory leverage to encourage harvesting.

Perspectives for HTO research

Key topics in this area, such as human interactions with technological evolutions (including more automation and new plant configurations such as multi-SMR units), are investigated in the Halden HTO project. It could be interesting to develop co-operation frameworks with external scientific communities in sectors other than the nuclear sector. Strengthening networking could be a good way to attract more organisations to the Halden HTO project, to gain additional insights from experts in other sectors and to identify other research capabilities.

Perspectives in fire research

Experience shows that fire is one of the greatest risks in nuclear facilities. Future research could consider investigations into fire risks in nuclear power plants under decommissioning, in research and demonstration reactors and in future reactors, including SMRs. Considering the wide range of possible topics, with different fire sources and configurations to investigate, it is necessary to establish research priorities in this area. As in the HTO area, it would be of interest to develop co-operation frameworks with external scientific communities in sectors other than the nuclear sector. Strengthening networking could be a good way to attract more organisations to fire research projects, to gain additional insights from experts in other sectors and to identify other research capabilities.

Perspectives for event database projects

Databases compiling international operating experience (e.g. CODAP, FIRE, ICDE [NEA, 2023b]) should be continued under the NEA as they provide high value data and information to the community. Such projects usually face the challenge that utilities may be reluctant to share data widely.

Increasing the membership of event database projects, with a larger participation by utilities, would be beneficial to the safety community.

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