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National Nuclear Safety and Waste Management Research Programme – SAFER2028

Framework Plan 2023–2028

Ministry of Economic Affairs and Employment of Finland

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Framework Plan 2023–2028

SAFER2028 Planning Group

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Abstract

SAFER2028 (National Nuclear Safety and Waste Management Research 2028) is a research program of the State Nuclear Waste Management Fund (VYR), the aim of which is to ensure that the authorities have the necessary nuclear safety competences and other prerequisites available for ensuring the safe use of nuclear energy and nuclear waste management in Finland.

The VYR -funded nuclear safety research programs should help maintain necessary knowledge for safe and economic use of nuclear power in Finland, develop new knowledge and facilitate participation in international cooperation. The various nuclear actors in Finland such as various ministries, the Radiation and Nuclear Safety Authority (STUK), power companies and Posiva have been able to utilize the knowledge and competences created in past research programmes.

The SAFER2028 research program also serves as a forum for discussion and communication between end users and research institutes in the nuclear field. The program will promote the development of national competence and research infrastructure development, ensure the continued availability of expertise, promote high-quality scientific research and increase public knowledge in the field.

The Framework Plan has been prepared by a planning group appointed by the Ministry of Employment and the Economy. The Framework Plan has been prepared for years 2023–2028.

Keywords	energy, nuclear energy, nuclear safety, nuclear waste management, research		
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Kansallinen ydinturvallisuuden ja ydinjätehuollon tutkimusohjelma SAFER2028: runkosuunnitelma 2023–2028

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Tekijä/t	Marja-Leena Järvinen ja Suvi Karvonen		
Yhteisötekijä	SAFER2028 Suunnitteluryhmä		
Kieli	englanti	**Sivumäärä**	131

Tiivistelmä

SAFER2028 (National Nuclear Safety and Waste Management Research 2028) on Valtion ydinjätehuoltorahaston (VYR) tutkimusohjelma, jonka tavoitteena on varmistaa, että viranomaisilla on saatavilla riittävästi ja kattavasti ydinteknistä asiantuntemusta ja muita valmiuksia, joita tarvitaan ydinenergian ja ydinjätehuollon turvalliseen käyttöön Suomessa.

Julkisten ydinturvallisuustutkimusohjelmien lähtökohtana on, että ne luovat edellytyksiä ydinvoiman turvallisen ja taloudellisen käytön jatkumiseen tarvittavan tietämyksen säilymiselle, uuden tietämyksen kehittämiselle ja kansainväliseen yhteistyöhön osallistumiselle. Alan tutkimusta Suomessa harjoittavat organisaatiot ovat olleet tärkeä voimavara, jota eri ministeriöt, Säteilyturvakeskus (STUK), voimayhtiöt ja Posiva ovat pystyneet hyödyntämään.

SAFER2028 -tutkimusohjelma toimii myös viranomaisten, ydinenergia-alan luvanhaltijoiden ja tutkimuslaitosten välisenä keskustelu- ja tiedonvälitysfoorumina. Ohjelmassa pyritään edistämään kansallisen osaamisen ja tutkimusinfrastruktuurin kehitystä, varmistamaan asiantuntemuksen jatkuva saatavuus, edistämään korkealaatuista tieteellistä tutkimusta ja lisäämään yleistä tietämystä ydinenergian ja ydinjätehuollon aloilla.

SAFER2028 runkosuunnitelma on laadittu työ- ja elinkeinoministeriön nimeämän suunnittelutyöryhmän toimesta. Runkosuunnitelma on laadittu vuosille 2023–2028.

Asiasanat	energia, ydinenergia, ydinturvallisuus, ydinjätehuolto, tutkimus		
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Nationellt forskningsprogram för kärnsäkerhet och kärnavfallshantering SAFER2028: ramplan 2023–2028

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Språk	engelska	**Sidantal**	131

Referat

SAFER2028 (National Nuclear Safety and Waste Management Research 2028) är ett forskningsprogram inom Statens kärnavfallshanteringsfond (VYR), vars syfte är att säkerställa myndigheternas tillgång till en tillräcklig och heltäckande kärnteknisk sakkunskap samt annan beredskap som behövs för en säker användning av kärnenergi och hantering av kärnavfall i Finland.

Forskningsprogrammet ska bidra till att upprätthålla nödvändig kompetens för säker och ekonomisk användning av kärnkraft i Finland, utveckla ny kunskap och underlätta deltagandet i internationellt samarbete. Organisationer som bedriver forskning inom detta område i Finland har varit en viktig resurs som olika ministerier, Strålsäkerhetscentralen (STUK), kraftbolag och Posiva har kunnat utnyttja.

SAFER2028 fungerar också som ett forum för diskussion och kommunikation mellan myndigheter, tillståndshavare och forskningsinstitut. Programmet syftar till att främja utvecklingen av nationellt kunnande och forskningsinfrastruktur, att säkerställa fortsatt tillgång på kompetent personal, att främja högkvalitativ vetenskaplig forskning och att öka den allmänna kunskapen inom kärnenergi och avfallshantering.

Ramplanen för SAFER2028 har utarbetats av en planeringsgrupp tillsatt av arbets- och näringsministeriet. Ramplanen täcker åren 2023–2028.

Nyckelord	energi, kärnenergi, kärnsäkerhet, kärnavfallshantering, forskning		
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Contents

PREFACE

An important precondition for the use of nuclear energy in Finland is the availability of national in-depth competence on nuclear safety and nuclear waste management safety. The commitment for maintaining a high level of national competence and building new capabilities for future challenges in Finland builds on continuous national research activities. This is the driving force in the development of the new nuclear safety and nuclear waste management research programme SAFER2028 covering the research needs until 2028.

We are now facing a new era in national safety research guided by the amendment of the Nuclear Energy Act in 2020. The ongoing nuclear safety research programme SAFIR2022 and the nuclear waste management research programme KYT2022 are integrated into one programme, SAFER2028, reflecting the responsibilities over the full life cycle. The integration of the ongoing multidisciplinary research programmes into one six-year programme brings benefits for the overall safety line of thinking and systemic approach to safety. The use of nuclear energy in Finland has facilities in all life cycle phases: at the design phase, in operation, under commissioning and under decommissioning, and it offers plenty of interfaces with opportunities for cross-cutting research themes. Moreover, high-level scientific activities are promoted, as a new feature, a Doctoral Education Network will be established in the SAFER2028 research programme.

Today and during the planning period of SAFER2028 we have faced several global crises that strongly resonate in the energy sector. First the battle against climate change is a vast challenge for energy production; second, the COVID-19 pandemic urged us to work remotely and locally, and third, the war in Ukraine pushes us to be more self-sufficient and independent of imports of energy. Thus, the importance of agility and resilience has been envisaged during the development of the Framework Plan for the SAFER2028 research programme. Despite these crises and new challenges, a common view of the future research needs and the way of conducting the programme were established together. The purpose of the national research programme, ‘To ensure national nuclear energy safety expertise over generations’, is clear and far-reaching. The commitment to further enhance the scientific level of research and integration into internationally relevant research programmes is also high.

The focus of research topics selected for the basis for the Framework Plan is set to the future with a positive fundamental idea. For planning purposes, the planning group updated the scenarios of the use of nuclear energy in Finland, from the Nuclear Energy Research Strategy in 2014, to build a common view of the future research needs.

Acknowledging uncertainties in the operating environment, a strategy that is based on a scenario between business as usual and nuclear breakthrough was chosen.

Nuclear energy is expected to play a significant and growing role in the Finnish energy system, and the Framework Plan offers the best estimate of research needs today. The impacts of the current war in Ukraine on the Finnish nuclear energy programme and further on safety research cannot yet be foreseen. As a result, from the actions to improve self-sufficiency and independence from Russian energy supplies, the significance of nuclear energy may increase, and the same may happen when answering to the sustainability criteria of the European Green Deal.

An independent international evaluation of the ongoing research programmes SAFIR2022 and KYT2022 confirmed the high scientific level of research and impressive results of the programmes. For the first time, the development of the new Framework Plan Draft was also assessed by the evaluation team simultaneously with the ongoing research programmes. The enriching insights of the high-level international team were valuable inputs to the Framework Plan and its further development.

The new SAFER2028 is expected to enhance the availability of nuclear safety expertise in Finland. National nuclear safety and national nuclear waste management research programmes are proven ways of maintaining and developing national competence in Finland. The key factors in achieving these goals are engaged stakeholders committed to safety research and active leadership of the programme.

The results of this joint effort form a solid and forward-looking basis for the new SAFER2028 research programme. In line with the Nuclear Energy Research Strategy, it will guide the national research on nuclear safety and nuclear waste management safety for the next six years and enable participation in EU and international research programmes in order to expand and share the national research themes.

In conclusion, I would like to express my sincere thanks to all those who participated in and contributed to this Framework Plan. In particular, I would like to thank the planning group and the writing groups for their vivid discussions and constructive attitude, and for working out the Framework Plan in a timely manner.

Marja-Leena Järvinen,
Chair of the Planning Group

May 2022

Abbreviations

ATF	Accident-tolerant fuel
BWR	Boiling water reactor
DSA	Deterministic safety assessment
EAC	Environmentally assisted cracking
ESRA	European Safety and Reliability Conference
ETSON	European Technical Safety Organisations Network
EURADSCIENCE	A Network of Research Organisations for Radioactive Waste Management Science Within Europe
EURATOM	European Atomic Energy Community
FIDES	Framework for Irradiation Experiments
FiR1	Finnish Reactor 1
HFE	Human factors engineering
HOF	Human and organisational factors
HRC	High radiological consequence
IAEA	International Atomic Energy Agency
IGD-TP	Implementing Geological Disposal of Radioactive Waste Technology Platform
IGRDM	International Group on Radiation Damage Mechanisms
I&C	Information and computation
KYT	Finnish Research Programme on Nuclear Waste Management
LILW	Low- and intermediate-level waste
LO1, LO2	Loviisa Reactors 1, 2
LUT	Lappeenranta University
LWR	Light water reactor
MEAE	Ministry of Economic Affairs and Employment
MG	Management Group
NEA	Nuclear Energy Agency
NWM	Nuclear waste management
OECD	Organisation for Economic Co-operation and Development
OL1, OL2, OL3	Olkiluoto Reactors 1, 2, 3
PPS	Physical protection systems
PRA	Probabilistic risk assessment
PSA	Probabilistic safety assessment
RE	Research organisation
SAFIR	Finnish Research Programme on Nuclear Power Plant Safety
SG	Steering Group
SHG	Stakeholder Group
SITEX	Sustainable network for Independent Technical EXpertise on radioactive waste management

SKB	Swedish Nuclear Fuel and Waste Management Company
SMR	Small modular reactor
SNF	Spent nuclear fuel
SRA	Society for Risk Analysis
SSM	Swedish Nuclear Safety Authority
STUK	Radiation and Nuclear Safety Authority
TAG	Technical Advisory Group
TSO	Technical support organisation
URC	Unacceptable radiological consequence
VTT	VTT Technical Research Centre of Finland
V&V	Verification & validation
VYR	National Nuclear Waste Management Fund
WENRA	Western European Nuclear Regulators' Association
YTERA	Doctoral Programme for Nuclear Engineering and Radio-chemistry
WMO	Waste management organisation

1 Introduction

1.1 Joint Nuclear Safety and Nuclear Waste Management Research Programme

The Ministry of Economic Affairs and Employment (MEAE) is initiating a six-year national technical and scientific research programme on the safety of nuclear power plants and nuclear waste management between 2023 and 2028. The new programme is a continuation of the series of government-led nuclear safety (SAFIR) and nuclear waste management safety (KYT) programmes that have proven their value in developing and continuously improving nuclear safety and nuclear waste management safety expertise for solving safety issues relevant to the Finnish use of nuclear energy. The safety research programme is based on Chapter 7a ('Ensuring availability of expertise') of the Nuclear Energy Act (990/1987). In essence, the programme covers the themes of the SAFIR2022 programme and KYT2022 programme that will both end in 2022. The abbreviation SAFER2028 is used for the new research programme. The programme is funded by the National Nuclear Waste Management Fund (VYR), as well as other key organisations operating in the field of nuclear energy. The annual VYR funding of the research in the ongoing SAFIR and KYT programmes has been approximately 10 million euros. The annual cost of the research of the ongoing programmes has been approximately 14 million euros. The VYR funding for the new programme is planned to increase from the SAFIR2022 and KYT2022 programmes funding based on the Nuclear Energy Act.

Independent expertise and knowledge-based decision-making in the nuclear sector has been considered crucial for the use of nuclear energy in Finland. National nuclear safety and nuclear waste management safety research programmes have played a significant role in building the in-depth expertise and the national capability in this field. To ensure the continuity of the research programmes, the Nuclear Energy Act was changed in 2003 and requirements for ensuring expertise were laid down. The holder of the Decision in Principle or the licencees of a nuclear power plant and those responsible for nuclear waste management (known as those liable for VYR payment from here on in this document) were obligated to pay fees for funding the research. Since then, Chapter 7a of the Nuclear Energy Act has been amended three times to reflect the need to adjust the fees collected and due to the major renewal of the national nuclear safety research infrastructure. The latest amendment in 2021 was to enhance research in cross-cutting topics throughout the whole life cycle of the nuclear facilities and the efficiency by merging the programmes. This integration of the programmes runs simultaneously to the changes in the national nuclear waste management programme, including Posiva's likely progress towards the operational phase.

The purpose of national nuclear safety and nuclear waste management safety research is to advance the safe use of nuclear energy and the development of nuclear waste management solutions. The need for expertise for the regulatory body, licencees and those responsible for nuclear waste management is acknowledged in Chapter 7a of the Finnish Nuclear Energy Act. However, the purpose of ensuring the expertise available for the regulatory body has not changed and it shall be guaranteed. The scope of the research expands from safety to safeguarding and security as appropriate in a public research programme. Chapter 7a's safety research is an essential part of the national framework ensuring adequate resources for the regulatory body and implementing the EU directive Article 5 paragraph 2 d published in 2014 amending the Nuclear Safety Directive. Paragraph 2 d deals with the competence of the regulatory body and the availability of expertise for technical support as necessary to fulfil regulatory obligations.

The organisational structure of the programme and the criteria for funding research are described in this Framework Plan of the SAFER2028 programme. Parliament stated that the funded research shall be multidisciplinary and on a high level internationally. Furthermore, the results shall be public, and international peer review shall be performed on the research. Parliament also acknowledges STUK's special position in steering the research with other stakeholders.

In 2021, the MEAE appointed the members of the planning group from the representatives of central organisations taking part in nuclear safety activities. The objective of the planning group was to produce the Framework Plan for the research programme and a proposal for its organisation. The planning group was authorised when necessary to supplement its expertise with permanent or temporary experts.

The planning group, consisting of 18 members including a secretary, started its work in March 2021. The planning group has supplemented its expertise by consulting experts and professionals from different organisations. The group assembled and worked as a single body, but several groups were formed to write up proposals, one for each research area of the upcoming programme, along with a special group to discuss the management structure and general topics. As part of the planning process, a workshop was held with 90 delegates in attendance. The work of the workshop groups laid the foundation for the content of the Framework Plan. The new research programme spans six years from the beginning of 2023. The MEAE will appoint the Management Group of the new research programme and will publish the call for proposals for the 2023 research projects in August 2022.

In December 2021, the MEAE announced a call for tender from organisations that could conduct the research programme's administration project, and chose the administration organisation and director of the new programme in May 2022.

In line with the Nuclear Energy Act Chapter 7a, the purpose and the vision were developed for the SAFER2028 nuclear safety and nuclear waste management safety research programme as follows:

Purpose:

> To ensure national nuclear energy safety expertise over generations.

Vision:

> The SAFER2028 research community is a vigilant and agile competence pool that carries out excellent and internationally attractive research on topics relevant to the safety of Finnish nuclear power plants and nuclear waste management facilities.

The research of the SAFER2028 research programme covers four principal research areas, a Doctoral Education Network and development of the national infrastructure for nuclear safety and nuclear waste management safety research. In Chapter 5 of this Framework plan, the scope and the goals of the SAFER2028 research programme and the necessary research are elaborated further.

1.2 Operating environment

1.2.1 Current status of the plants and licensing issues

At present, the nuclear industry in Finland is very active. Currently, there are nuclear facilities in all life cycle phases: in the design phase, in operation, under commissioning and under decommissioning. The long-term commitment is reflected in the planning of the activities reaching out to the middle of the next century. The current view of the overall schedule of the nuclear facilities is presented in Figure 1.1. A third (35% in 2019) of the electricity produced in Finland comes from nuclear energy. As for electricity consumption, more than a quarter (27% in 2019) is produced with Finnish nuclear energy. In the new climate and energy strategy, nuclear power plays an important role in achieving carbon-free zero emission targets by 2035 and beyond.

The nuclear power plant units LO1 and LO2 at Loviisa have an operating licence that is valid until 2027 and 2030, respectively. Currently, the operator Fortum Power and Heat Oy

(Fortum) is applying for an extension to the operating licences until the end of 2050, but the decision has not yet been made. The immediate decommissioning will follow the end of operations of units LO1 and LO2. Currently, the periodic safety review of the nuclear power plant units is ongoing. The interim storage of the spent fuel is included in the operating licence of a nuclear power plant. At the same time, the periodic safety review of the Loviisa low- and intermediate-level waste repository (LILW repository) was completed. The aim is to renew the operating licence of the repository in the near future to include the decommissioning waste of Loviisa nuclear power plant and the FiR 1 research reactor as well. Moreover, the plan is to add the possibility to dispose of small amounts of radioactive wastes from industry, hospitals and research facilities in the Loviisa LILW repository. Currently, the LILW repository has an operating licence until 2055. Alongside the application for continuing the operation of the NPP, Fortum has also applied for an extension of the LILW repository licence until the end of 2090.

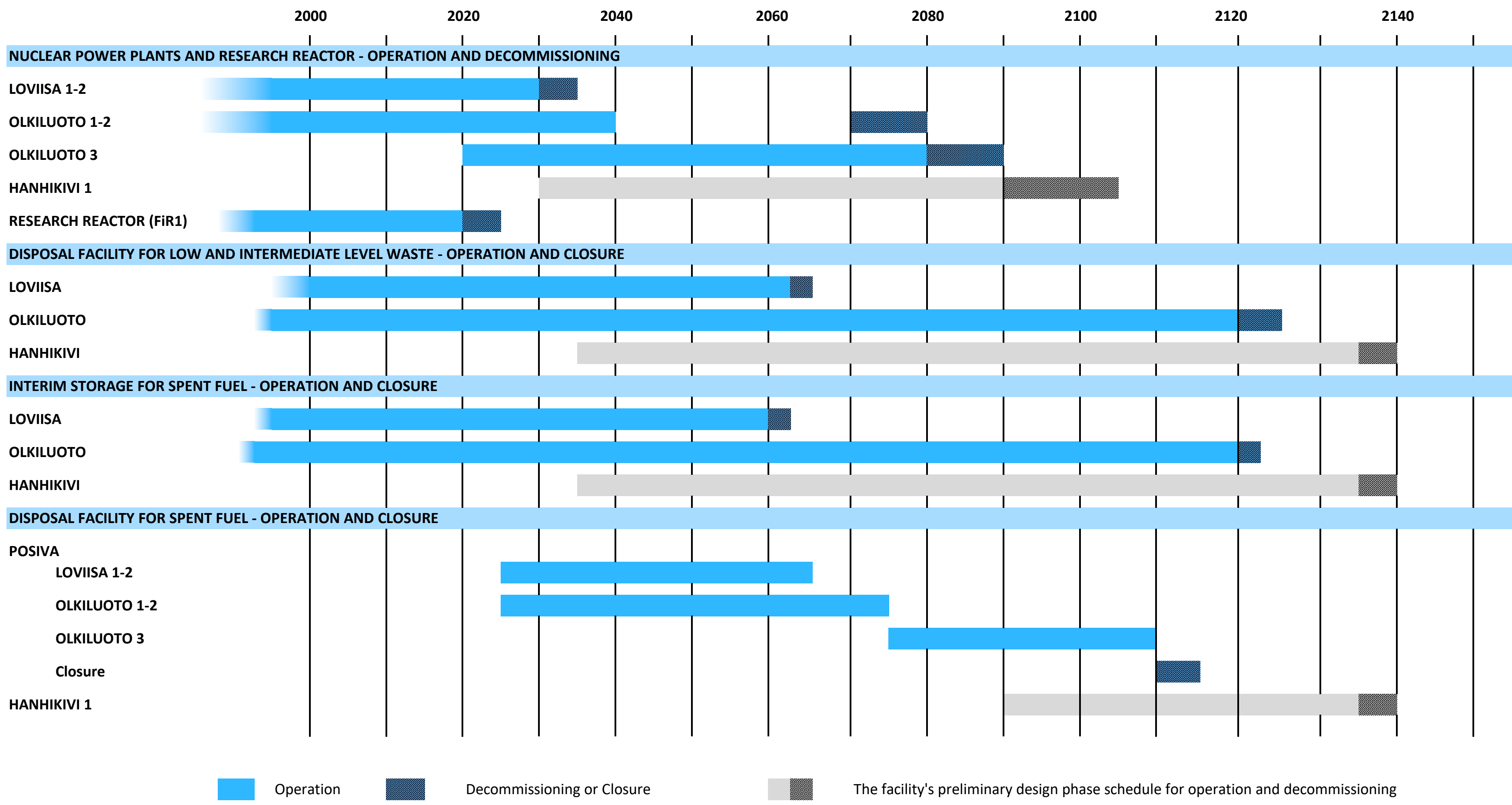
The operating licences for nuclear power plant units OL1 and OL2 at Olkiluoto are valid until 2038. They are planned to be dismantled by a deferred dismantling strategy in the late 2070s. Unit OL3 has a valid operating licence until 2038. The first criticality of OL3 took place on 21 December 2021. According to the current plans, the immediate decommissioning of OL3 will start in the 2080s. The interim storage of spent fuel will operate until all spent fuel is disposed of. The repository for low- and intermediate-level waste in Olkiluoto has an operating licence until 2051. In addition, TVO is planning to construct a near-surface repository for the disposal of very low-level waste disposal. The licensing of this facility will start at the earliest at the end of 2022.

The nuclear power plant unit at Pyhäjoki, Hanhikivi (FH 1), is in the construction licence phase. There is an overall plan to construct an interim spent fuel storage, a repository for low- and intermediate-level waste, and a near-surface repository for very low-level waste at the Hanhikivi site. The project time schedule will be specified as it proceeds.

The research reactor FiR 1 is in the decommissioning phase. The licence for decommissioning was granted by the government in June 2021. According to the current schedule, the dismantling will start at the end of 2022 and the site will be released from regulatory control by the end of 2023.

The construction licence for the Posiva encapsulation plant and the final disposal facility of spent fuel was granted by the government in 2015, and the construction of the facilities started in 2016. Posiva submitted the operating licence application for the final disposal facility of spent fuel at the end of December 2021. The operation of the facilities will continue until all spent fuel from the nuclear power plant units LO1-2 and OL1-3 have been disposed of, i.e. up to the 2120s. After this, the encapsulation plant will be dismantled and the final disposal facility will be permanently closed by the end of the 2130s according to the current licensing plans.

Figure 1.1. Status of nuclear projects in Finland at the end of 2021.



1.2.2 Renewal of the Nuclear Energy Act and related regulations

The 1987 Nuclear Energy Act provides conditions for all of the licences of nuclear installations and all the operators' responsibilities. This law has been written with large light water reactors providing electricity in mind. It has been amended and changed several times over the decades to meet the requirements of the operating environment, EU directives, and changes in parallel legislation e.g. the Radiation Act.

Today it is evident that the Nuclear Energy Act needs to be renewed to meet the legislative requirements and the approaches to the law writing of today. There is also a need to meet the requirements and terminologies of EU directives. As a future need, the regulations and the licensing process needs to be evaluated in respect of the new small modular reactor (SMR) technologies and e.g. for heat production as well. The schedule of this renewal work is anticipated to take one term of office for the government, meaning that the new legislation could be in force by the end of 2027 at the earliest.

The renewal of the STUK regulations and the YVL Guides will be carried out in parallel with the renewal of the Nuclear Energy Act and Decree. The safety level of the Finnish legal framework was enhanced after the Tepco Fukushima Daiichi nuclear power plant accident in 2011, and therefore there is no need to change the current level of safety requirements. However, binding requirements shall be presented in the Nuclear Energy Act, the Nuclear Energy Decree and in the STUK Regulations according to the principles laid down in the Finnish Constitution, and the status of the YVL Guides will change to explain and justify the requirements. In the future there might be examples of solutions in the YVL Guides, and their format may change from a publication to a database solution. The updating of the International Atomic Energy Agency (IAEA) safety standard requirements and the Western European Nuclear Regulators Association (WENRA) reference levels are considered systematically in preparation of the STUK regulations.

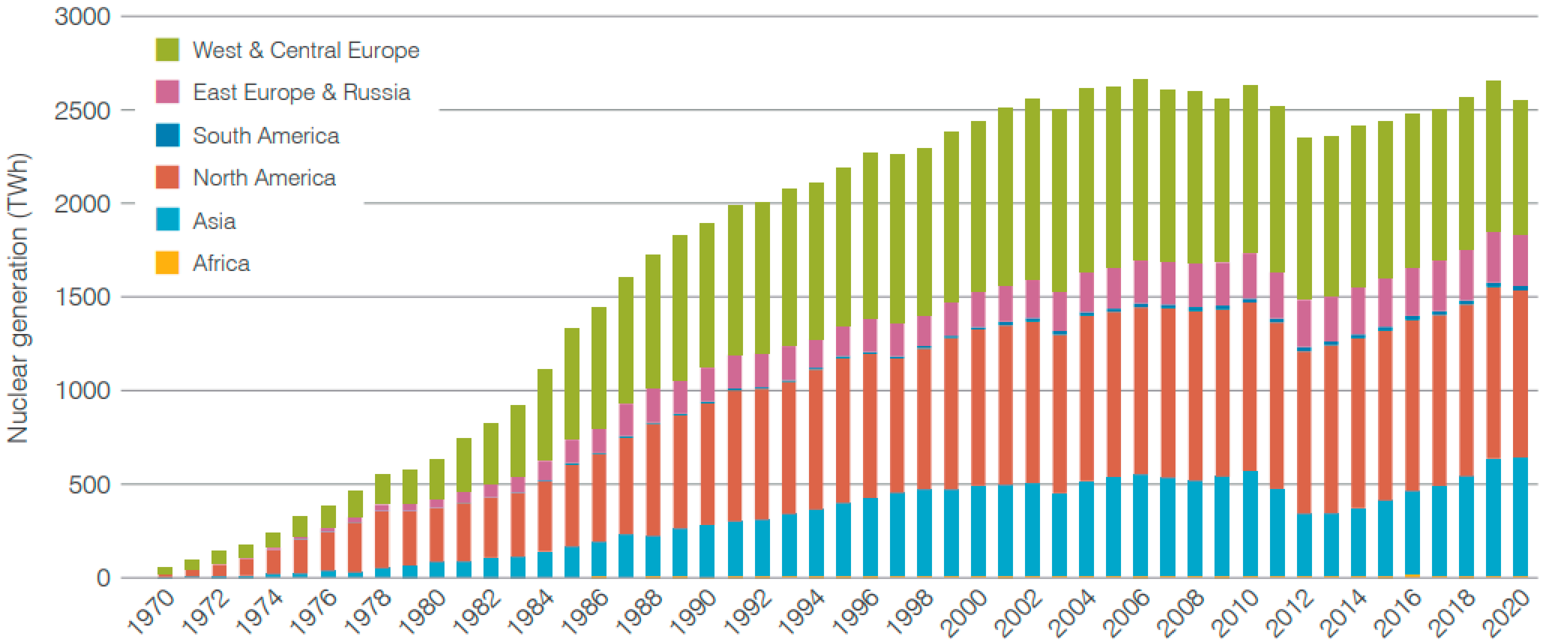
The first goal of the renewal of the STUK regulations and YVL Guides is to emphasise the licensee's responsibility for safety that is required by the Nuclear Energy Act. This obligation cannot be delegated to another party, and it also covers subcontracted activities. STUK's strategy emphasises the licensee's responsibility for safety, and the development of STUK's future oversight is underway.

Another goal of the renewal of the STUK regulations and the YVL Guides is to enable more fluent licensing of different kinds of technologies and implement flexibility in demonstrating the safety of a nuclear facility or systems, structures and components important to safety. This is achieved through goal setting and technology-neutral requirements, which will be applied as far as possible. The licensing of the current type of nuclear power plants and emerging technologies, e.g. SMRs, will be considered in the STUK regulations.

1.2.3 Nuclear energy scenarios

The development of nuclear energy has been a story of three main phases: 1) the rapid expansion of nuclear energy, mostly in the Western world, from the 1970s to the 1990s, fuelled by new technology, growth in energy demand and the energy crisis; 2) a phase of comparative stagnation from the 2000s to the 2010s during the rapid expansion of gas-fired production; and 3) since the 2010s, a phase of expansion in the developing world and a continued stagnation in developed countries.

Figure 1.2. **Nuclear energy generation in the world 1970–2020.**



Source: World Nuclear Association and IAEA Power Reactor Information Service (PRIS)

For the future, a variety of possible paths for the use of nuclear energy are suggested by different organisations. The IPCC 1.5-degree report's[1] illustrative scenarios imply a growth of between 59% and 106% from 2010 levels to 2030, and a growth of between 97% and 501% to 2050 as part of the solution to climate change.

To understand the needs of the SAFER2028 programme for the longer term, different pathways should be considered as there is a lot of uncertainty in the future of nuclear energy. Based on the work done for the national nuclear energy strategy[2] 2014 update in 2020 and a look back at the main trends in various countries in the past, five scenarios were identified:

1) Business as usual

This scenario represents an anticipated future without any major surprises. Worldwide, new-build nuclear construction continues to take place in the developing world, while long-term operation of the existing fleet and decommissioning takes place in developed economies. The use of electricity is expanding rapidly globally, mainly driven by variable renewable production. In Finland, the operating plants continue their lives towards 2050, and ongoing projects are proceeding as planned. No major new projects are due to start in Finland.

2) Cost escalation

This scenario represents a world where the operating and construction costs for nuclear energy start or keep growing. Simultaneously, alternative energy sources have a favourable development, wind and solar keep decreasing in price, and storage and power-to-X technologies keep the systems working. In Finland, the operating plants are under threat of early closure due to cost competitiveness, and costs to construction of ongoing projects keep rising. No new major investments in nuclear energy look feasible and competencies start shrinking with cost cuts.

3) Nuclear breakthrough

In this scenario, new nuclear technologies under development succeed in their goals. Around the world various new-build projects, many in SMRs, are started and completed

1 IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty.

2 National nuclear energy strategy, MEAE: TEM_jul_16_2014_web.pdf

successfully. New demand in component manufacturing and competencies improve the competitiveness of existing plants. Legislation and harmonisation proceed to develop favourably. Demand for new waste solutions is high as new countries start using nuclear energy. Market-based SMR investments accelerate in Finland in the 2030s and various end-uses for the energy are common.

4) European phase-out

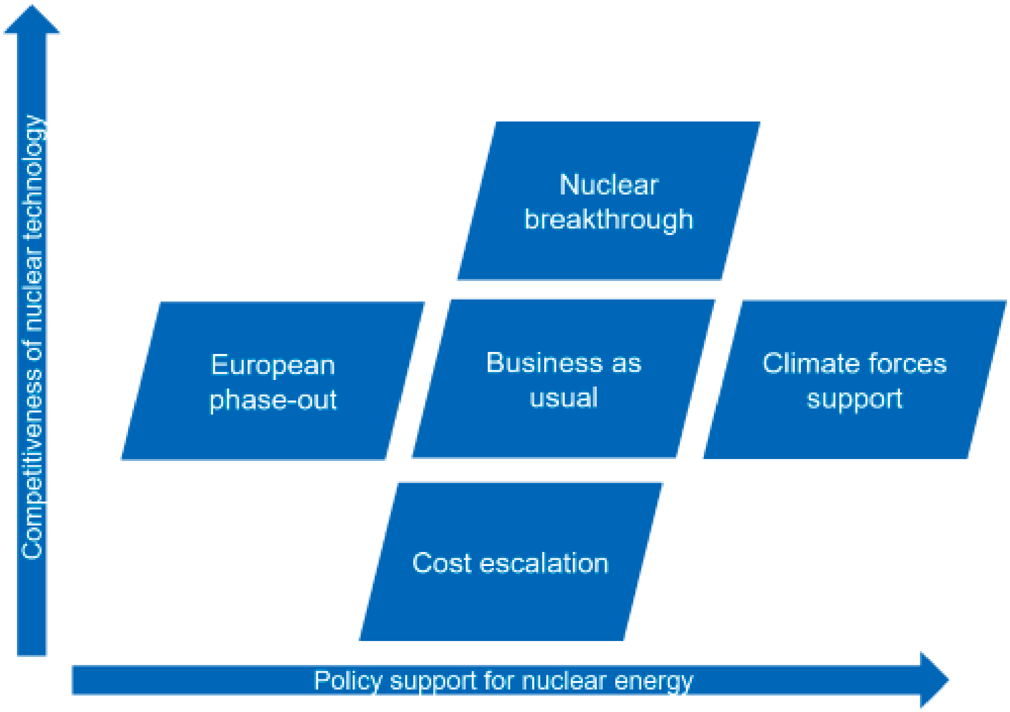
In this scenario, after a significant public incident of some kind, support for nuclear energy drops sharply worldwide. The industry turns to focus on the causes and aftermath of the incident. Regulators work hard to develop their requirements to meet the strong public demand for increased regulation. Additional investment needs for operating plants surface and ongoing projects are delayed with design changes due to the incident. Public opposition to new nuclear energy and waste solutions increases and forced premature shutdowns to take place in various countries.

5) Climate forces support

In this scenario, after a sustained failure to meet climate goals with existing policies, an ambitious strategy to decarbonise with nuclear energy is taken in many countries. New projects are started with existing accessible technology in many countries with political involvement. There is strong growth in the demand for nuclear resources.

The five scenarios represent the main dimensions influencing the future of nuclear energy worldwide and in Finland, competitiveness of the technology, and policy support, and can be placed in a matrix (Figure 1.3).

Figure 1.3. Five scenarios identified for nuclear energy development in the long term.



The five scenarios represent possible long-term development trends in the industry. For the purposes of SAFER2028, a strategy based on the analysis should be selected. In the short term, the most likely path forward is Business as usual. Because scaling knowledge and resources upwards is more difficult and slower than scaling down, a positive turn of events is a safe choice. For surprising events, it has been proven that society can switch focus according to topical questions. When considering the two positive development paths, Climate forces support is more of the same and the skills and infrastructure for that scenario already exist. However, in the Nuclear breakthrough scenario, more novel topics can be expected. Still, the most important and least uncertain needs are current facilities and projects. Thus, for planning research to be carried out in SAFER2028, a strategy that is based on a scenario between Business as usual and Nuclear breakthrough was selected. The resulting optimistic and forward-looking research topic selection has been used as the basis for the Framework Plan.

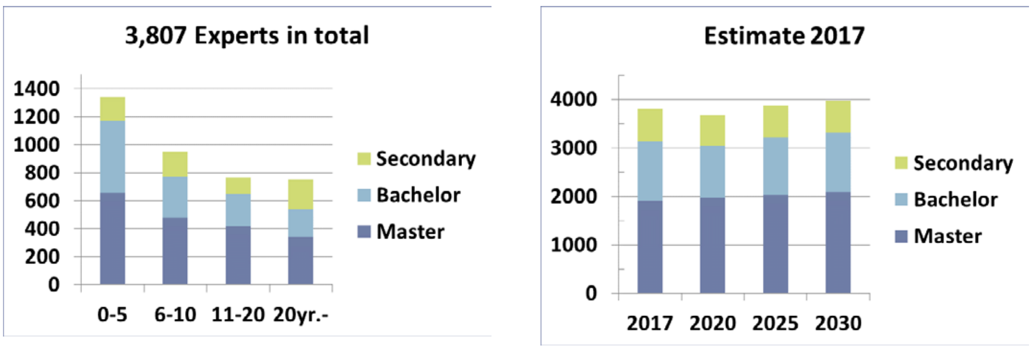
1.3 Expertise and future needs

The second survey of competence in the nuclear energy sector was carried out in 2017. The following selected organisations were invited to complete a questionnaire online:

key nuclear-sector actors, universities and universities of applied sciences, and industries closely associated with nuclear energy.[3],[4] Over 20 critical competencies were identified in the field of nuclear energy use.

In total, the number of experts reported in the survey was 3,807. The distribution by years of experience concentrated around younger experts (Figure 1.4, left). On the whole, Master's and Bachelor's degree holders account for 50% and 32%, respectively, while the remaining 18% have a secondary-level vocational qualification. In total, there were 1,895 Master's degree holders in 2017, 32% of whom worked for power companies or Posiva, while those employed by public authorities, universities or research institutes and other industrial companies accounted for 8%, 26% and 34%, respectively. Some 18% of Master's degree holders held a postgraduate degree (i.e. a doctorate or a licentiate).

Figure 1.4. Left: Number of experts by years of experience (0–5 years, 6–10 years, 11–20 years and over 20 years in the nuclear energy sector) and by educational qualification (secondary-level vocational qualification, bachelor's degree and master's degree) in 2017. Right: Number of experts in 2017 (left) and estimated demand for future years by educational qualification (secondary-level vocational qualification, bachelor's degree and master's degree).



In 2017, demand for experts was estimated to decrease slightly in the near future, followed by a slight upturn (Figure 1.4, right). Demand for personnel was estimated to be 3,981 in 2030, which is 5% higher than the number of personnel in 2017. The experts

3 Hämäläinen, J. & Suolanen, V., 2017, Survey of Competence in the Nuclear Energy Sector 2017–2018 (Ydinenergia-alan osaamisselvitys 2017–2018; in Finnish). VTT Technology 344. Espoo 2018. 66 p + 6 app. ISBN 978-951-38-8676-9. https://www.vtt.fi/inf/pdf/technology/2018/T344.pdf

4 Hämäläinen, J. & Suolanen, V., 2019, Survey of Competence in the Nuclear Energy Sector 2017–2018 in Finland. Publications of the Ministry of Economic Affairs and Employment. Energy 22/2019. 85 p. ISBN: 978-952-327-410-5. http://urn.fi/URN:ISBN:978-952-327-410-5

with a bachelor's degree and secondary-level vocational qualifications were expected to suffice, while additional demand consisted of master's degree holders. According to the survey, the number of master's degree holders should increase by 190 individuals, i.e. 10% from 2017 levels to the need in 2030. The survey also showed the estimated demand of experts for different competence areas as a whole and separately for public authorities, as well as for power companies and Posiva. A survey of nuclear waste management-related competencies is planned for 2022.

The SAFER2028 research programme is the most important instrument in Finland for educating new experts for the increased demand for master's degree holders as well as for the replacement of experienced experts who retire. A sufficient level of experts holding a doctorate can only be held by providing sufficient funding and guidance, which is very hard to achieve by other means than in national programmes on nuclear safety and nuclear waste management safety. Doctoral education subjects are discussed further in Chapter 3.

A strategy based on a scenario between business as usual and nuclear breakthrough offers an interesting platform for the national competence-building and resilient expertise for future needs.

1.4 Role of national research programme in nuclear safety knowledge management

The national research programme supports the capturing of knowledge and its transfer between organisations and generations through carrying out internationally high-level multidisciplinary safety research on topics relevant to the use of nuclear energy in Finland. SAFER2028 includes knowledge management to deliver strategic objectives dedicated to the enhancement and transfer of knowledge between generations and organisations: It will be taken into account at all working levels that publicly available knowledge generated in past, ongoing and future research, development and demonstration activities is preserved and made accessible. Different types of knowledge are embedded in the wide range of SAFER2028 products, such as publications, analysis tools and methods, data asset and infrastructure, SAFER2028 processes, and experts involved in the steering and carrying out the research. International cooperation and publication of the research results in scientific journals further aids the preservation of knowledge and facilitates access to international state-of-the-art know-how. The transfer of silent know-how is ensured through continuity and involvement of experts at different professional career phases working together on the same projects.

The preservation/capitalisation of generated knowledge ensures that this national programme takes advantage of existing knowledge and know-how at an early stage of implementation from the organisations, primarily to access the state of the art, and second, to ease access to knowledge developed during previous SAFIR and KYT programmes.

It shall be ensured that the necessary expertise and skills are maintained through generations of experts given the long lead times and operational timespans (several decades) for radioactive waste management, including disposal, by providing training and mobility for researchers.

Measures to further enhance the management of knowledge developed in the national programme will be developed in the administration of the SAFER2028 research programme.

1.5 Programme objectives

In this chapter, the programme-level objectives of SAFER2028 are discussed per research area. The four thematic research areas are:

- Overall Safety and Society
- Reactor Safety and Fuel Cycle
- Nuclear Waste Management, Final Disposal and Decommissioning
- Structural and Mechanical Safety of NPPs

These research areas of SAFER2028 are discussed in detail in Chapter 5.

The main objectives of each research area are discussed in the following subchapters. The programme objectives have been chosen based on the strategic scenario selection discussed in Chapter 1.2. – Business as usual and Nuclear breakthrough leading to the optimistic and forward-looking selection of key research topics, as discussed below.

1.5.1 Overall safety and society

The overall safety and society research area includes a wide range of overarching nuclear safety research topics. The main research topics include the overall safety concept itself, societal aspects of nuclear energy (acceptance, risk perceptions, regulation, trust), systems engineering approaches for nuclear facilities, risk assessment and risk-informed decision-making, empirical and theoretical research in human factors, organisational factors, safety culture and leadership. The objective is to facilitate the development of methods and approaches that take the systemic nature of safety into account when safety is assessed and improved.

The overall safety concept is an umbrella for safety thinking throughout the whole nuclear life cycle. Safety is a principal basis for all activities in nuclear energy and nuclear waste management, and it is a prerequisite for societal acceptance of nuclear energy usage in society. Understanding the different aspects and areas of safety needs to be further studied to better establish the concept of overall safety. One of the key principles to be considered is the risk-informed graded approach, which should mean consistent decision-making commensurate with the risks posed by a nuclear facility. The practical implementation of a graded approach in different safety management contexts is, however, often far from self-evident, which means that understanding and highlighting the graded approach principle is expected in the research projects.

1.5.2 Reactor safety and fuel cycle

The main objectives in the research area related to reactor safety and fuel cycle (section 5.2) are to maintain and further develop the available nuclear safety analysis expertise and capabilities. This requires a profound understanding of nuclear technologies, relevant phenomena and analysis methods, as well as availability of flexible analysis tools and experimental research facilities. One key issue is the proper validation of analysis codes, resulting in a quantified understanding of their reliability and applicability, also extending to analysis chains where the results are carried over from one code to another. Experimental research, in addition to its ability to shed new light on safety-relevant phenomena, provides essential data for code validation and may help to extend the use of existing tools to new application areas better serving the safety of the whole fuel cycle.

The expected future developments and changes in the operating environment are likely to impose new demands and challenges on the use of nuclear energy, but also provide new possibilities, e.g. in the form of new materials and technologies. In order to support the continuous safe use of the nuclear facilities currently in operation or under development and to be able to take full advantage of the new possibilities, the research activities need to be able to adapt to new situations and to keep providing advanced tools for the development and demonstration of nuclear safety.

1.5.3 Nuclear waste management, final disposal and decommissioning

The objective of the research area is to promote the safe use of nuclear waste facilities and the development of solutions for the management of nuclear waste. The objective is also to ensure that adequate and comprehensive expertise and other skills are available to authorities and those liable for VYR payments under waste management obligations. In addition, the goal of the research area is to support and complement the research programmes of the licensees under waste management obligations, and to further develop both national and international collaboration between authorities, waste management organisations and researchers.

The research area of nuclear waste management includes all waste streams from very low-level waste to spent fuel. The research will target the pre-disposal treatment of radioactive waste, final disposal of nuclear waste and topics arising from decommissioning.

In SAFER2028, central topics within the research area of nuclear waste management are:

- Final disposal of low- and intermediate-level waste (LILW), including new materials arising from decommissioning activities.
- Total disposal system performance over the long term and especially the interactions within and between the interfaces of bedrock, overburden, groundwater and engineered barrier systems (EBS).
- EBS, other structures and their combined performance; possible modifications and optimisation of the final disposal concepts arising from operational experience.
- Decontamination and minimising the generation of secondary waste during decommissioning, and the pre-disposal treatment of radioactive waste in general.

1.5.4 Mechanical and structural safety of NPPs

The research area connects structural safety and materials to a research entity that benefits from expert collaboration, and that can form a broader view of plant life cycle management. A particular goal is to secure the necessary knowledge and expertise to support the existing Gen II plants in operation, and conduct method validation.

The aim of the research is to increase knowledge that supports the long-term and reliable use of nuclear power plants, particularly with respect to matters involving the integrity of barriers or material issues that affect the reliability of the safety functions. The research will target the ageing phenomena of the existing equipment and structures, and the correctly timed management of their progress.

The research topics are grouped into the following main areas: ageing management (primary and secondary system components, civil structures, other system structures and components), new methods and materials (non-destructive testing, monitoring, small modular reactors, additive manufacturing); and safety-relevant loads (fragilities, seismic hazards, fire safety engineering, validation of methods and tools).

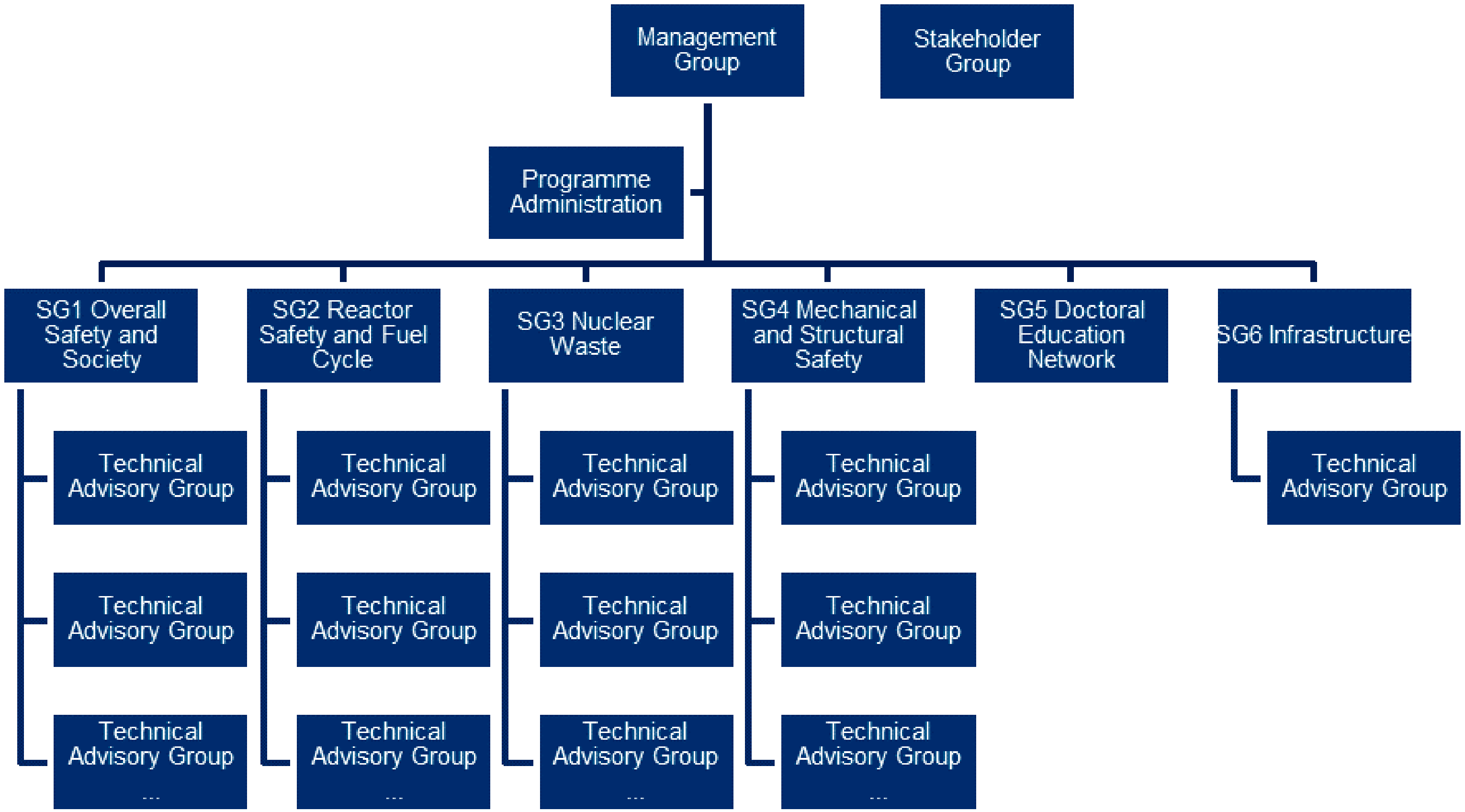
2 Administration

2.1 Programme administration

The programme's operating model consists of a Management Group (MG) and six research area Steering Groups (SG) working under its supervision, as well as Technical Advisory Groups (TAG) that are responsible for scientific and technical guidance of the projects (Figure 2.1). The administration of the programme is conducted by the administrative unit and the programme director, appointed on the basis of competitive bidding. Additionally, a Stakeholder Group (SHG) will be created to give research organisations and possible other stakeholders an overview of the research programme activities and an opportunity to present their views to the MG. The SHG and MG can arrange joint meetings.

Research will be carried out in projects led by project managers. The research topics of the projects may be related to one or more research areas but administratively each project will be placed in one research area. Projects are also placed in a TAG assigned by the research area SG, if the SG sees that technical steering is required. The Doctoral Education Network and infrastructure projects and activities are handled in their own SGs.

Figure 2.1 **Structure of the programme's administration. Each project belongs to one Steering Group, but its topic may be related to one or several research areas. The Technical Advisory Groups of the SAFER2028 programme will be defined once the programme has started.**



The administrative practices of the research programme will be described in detail in the SAFER2028 operational management handbook. The principle of independence will be applied when selecting and monitoring the projects. Therefore, a person working on a project cannot be a member of the programme's SG or TAG group in question.

The MEAE will appoint a Management Group for the programme that includes representatives of central end user nuclear safety organisations. The MG will nominate the TAGs based on the proposals set by the SGs. The MG also appoints the chairpersons and members of the SGs and TAGs. A special TAG will be appointed for the development of research infrastructure. A special SG will be appointed for steering the Doctoral Education Network. There will be a special Stakeholder Group (SHG) for direct communication between the MG and the research community. It will hold a joint meeting 1–2 times a year.

2.1.1 Management Group

The Management Group (MG) is responsible for the programme as a whole and its results, so that the programme meets the statutory requirements. The MG also decides on the project portfolio, monitors the implementation of the research programme and updates the Framework Plan for each call for proposals, if needed. The MG prepares a proposal for the MEAE on the projects for the next year, and the MEAE will prepare a statutory funding proposal to VYR after receiving a statement from STUK.

The chair and one or two representatives of the MG are appointed from the Radiation and Nuclear Safety Authority (STUK), with preferably nuclear power and waste expertise both included. The director of the programme acts as the secretary. One representative from each power company in the nuclear energy sector as well as Posiva will be selected for the MG, along with a representative from SSM (Swedish Nuclear Safety Authority, Strålsäkerhetsmyndigheten) and the Ministry of Economic Affairs and Employment (MEAE), the Ministry of the Environment, and the Ministry of Social Affairs and Health. The MEAE contact person will also serve as VYR contact person. A deputy member will be appointed for each member. The participating organisations will cover the participation expenses of their representatives.

In the MG decision-making, questions related to topics that are crucial to the research organisations such as IPR of the research results, publication restrictions, etc. should be handled with care. The questions should be discussed in the SHG and its opinion should be considered in MG decision-making.

The MG will meet when needed and, as a general rule, three times a year.

2.1.2 Steering Groups

The research area Steering Groups (SG1–SG4) and the infrastructure Steering Group (SG6) are responsible for the content and results of the research programme in their respective fields; they prepare the calls for proposals for their fields, and evaluate research project proposals and place the projects in the TAGs. The groups also promote the emergence of multidisciplinary research projects and are responsible for updates to the research areas' plans and annual areas of focus. An SG can propose the establishment of a new TAG in its own area and also propose multidisciplinary groups to the MG. The Doctoral Education Network SG (SG5) is somewhat different from the other SGs, as it focuses on ensuring high scientific quality of the doctoral projects as well as organising activities for the network.

The SGs are responsible for monitoring the research projects in their fields and for reporting to the MG. They also rely on the competence of the TAGs when monitoring the progress of research in the projects and when otherwise necessary. The SGs must ensure that the achieved results and realised costs of the projects are in line with the funding decisions. An SG will approve changes in the project plan when they are substantial or require changes in the budget. An SG also approves the corresponding budget changes.

The chairs of the SGs for research areas (SG1–SG4) are appointed from STUK and the director of the programme acts as the secretary. In SG5 and SG6 the chair can be from any participating organisation. One representative from each power company in the nuclear energy sector as well as from Posiva will be appointed to each SG. A deputy member will be appointed for each SG member.

The SGs will meet when needed and, as a general rule, two times per year. The results of the research projects from the preceding year and the updated project plans of the commencing year will typically be assessed in March, and the proposals for the next year are evaluated in November.

2.1.3 Technical Advisory Groups

The Technical Advisory Groups (TAG) are responsible for the scientific and technological guidance of the research and infrastructure. They also decide on necessary changes in project plans concerning the research content as the work progresses when the changes do not require changes in the project budget or are not substantial. The members of the TAGs may evaluate the scientific level and content of the research project proposals upon request of the SG of the research area.

The MG will confirm the research topics and composition of each TAG on the basis of the proposal of the SG of the research area. New TAGs can be set up and old ones terminated during the programme.

The chairperson of a TAG is a representative of a nuclear power company, Posiva or STUK, or another recognised expert in the field. Its secretary will be a project manager on a rotational basis. Experts will be appointed to the Technical Advisory Group so that each nuclear power company, Posiva, STUK and the research organisations responsible for the projects in the group are represented by at least one person; when necessary, other experts may be included.

Minutes are prepared of the TAG meetings on a rotational basis by the project managers. Any decisions concerning the content of the projects and the proposals to be made to the SGs or the MG will be documented in the minutes. The minutes will be distributed to the MG, the SGs, the TAG and the project managers in question. The TAGs will meet when needed and, as a general rule, two or three times a year. Ad hoc meetings are recommended when beneficial.

2.1.4 Programme director and administration organisation

The programme director and the administrative organisation are responsible for the administration of the programme. They are chosen on the basis of competitive bidding. The duties of the director and the administrative organisation are specified in a contract. A project coordinator and other assistants assist the programme director in the administration and the project coordinator may also act as a substitute in the meetings if necessary. Assisting staff of the administrative organisation also participate in meeting and seminar arrangements, updating the website, etc.

The director and the administrative organisation prepare the meetings of the MG and implement its decisions, maintain the programme's website, take care of international cooperation at the programme level, and promote international collaboration. The programme director and the administrative organisation also prepare topics to be discussed in the SG meetings and see to the coordination between the TAGs and projects.

Twice a year (at the end of October and January), the programme director and the administrative organisation collect cost summaries and content-based progress reports on the projects assessed by the TAGs for the SG meetings in order to assist the approval of the invoicing. The programme director participates in the meetings of the MG, SGs and TAGs.

The director and the administrative organisation prepare the annual report, the interim report, the final report and other required reports, and follow up on costs to serve as a basis for invoicing VYR. The administrative organisation co-ordinates the annual call for proposals for VYR-funded projects in accordance with the guidance of the MEAE and the MG.

The programme director and the administrative organisation promote and present the programme, develop its activities, and maintain an operational management handbook and other guidelines internal to the programme.

The programme director and administrative organisation of the programme organise an interim and a final seminar as decided by the MG, as well as other common functions of the programme.

The programme director and the administrative organisation also assist the MEAE in other tasks related to the programme.

2.1.5 Stakeholder Group

The Stakeholder Group (SHG) consists of representatives from the research organisations and possible other stakeholders. The chair of the SHG is a senior-level expert, possibly appointed on a rotational basis. The SHG will have an overview of the research programme activities and it is an established forum for the research organisations to provide their views and input to the MG. The SHG and the MG arrange joint meetings, and information and results can be shared at a general level in addition to the communication taking place in the TAGs.

In particular, the SHG organisations have a veto right on decisions that address the use of their research infrastructure, the organisation's own funding, IPR etc., in a way that is not accepted by the respective stakeholder organisation.

2.2 Projects and procedure for calls for proposals

The research projects in the programme shall have ambitious goals and be of high quality by international standards. Project objectives can be application-oriented or they can develop and maintain competencies recognised as important in the Framework Plan. Applied projects may create new scientific results or bring known results into practical use in a new way. Projects that develop and continuously improve the competencies ensure that Finland has the necessary expertise, including up-to-date validated methods and experimental facilities, for the safe use of nuclear energy and the safe management of nuclear waste.

The project plans should demonstrate the novelty of the research, show how the project will strengthen the overall nuclear safety and the Finnish competences in nuclear safety, and promote international networking and collaboration among the actors in the area. The application of practices from other industries may also be a suitable research topic. Doctoral theses demonstrate the qualifications of the researchers and the scientific novelty of the findings. In addition to these, the work must also be significant for the research programme. General participation in international cooperation or networking, and the organisation of international seminars, etc. are not funded by the research programme.

Clear goals and tasks must be set for each project to be funded in the programme. The SGs must also be able to assess how the goals have been met during the project year and at its end. The plan for each project year must contain interim goals that can be assessed at the end of October and the goals for the entire project year that are assessed at the end of each project year in January.

2.2.1 Different project types in SAFER2028

The research programme can have projects of different types in length, number of participating organisations and objectives:

- Research projects lasting one or several years that apply for funding annually
- Excellence projects lasting two or more years with funding granted for the entire duration of the project
- Doctoral education projects for postgraduate students receiving funding from SAFER2028 for their doctoral studies as described in Chapter 3, with funding granted for the entire duration of the project
- Complementary education projects for further training of experts in nuclear energy and waste-related subjects
- Small studies are started by the MG outside of the call as contract projects
- Projects for improving nuclear energy research infrastructure in Finland. Infrastructure funding can also be included in any research project. It is recommended that there is collaboration with other research organisations, with mutually accepted conditions.

The majority of the projects will be research projects. It is recommended to start new innovative topics with bigger risks as one- or two-year projects. The MG may annually reserve a certain proportion of the available VYR funding for one- or two-year research projects and small studies. Longer projects shall focus on competencies that have already been recognised as important for nuclear safety in Finland. Doctoral theses can be included as part of a longer project.

Excellence projects are larger and shall have a high scientific level. The project plans shall be sufficiently detailed for multiple (3–6) years. Excellence projects do not apply for funding separately for each year except when significant changes to the original plan are made. If problems in the progress of an excellence project are identified by an SG, an update to the research plan and submission of the proposal may be required to the same funding consideration as normal research projects. Excellence status may be applied for the proposal, and it can be either approved or declined by the MG. Excellence status is granted only to selected projects in the programme.

It is also possible to propose a project to arrange complementary education for further training of an expert or a group of experts in nuclear energy- and waste-related subjects without actual research objectives.

In addition to the actual research projects, the SAFER2028 MG can annually initiate small studies as contract projects with the order procedure. Decisions on the small study projects will be made after the evaluation of the proposals for the annual call. The small study projects will support the implementation of the Framework Plan in topics that are not covered by the actual research projects. They can also introduce new topics.

2.2.2 Call for proposals and funding decisions

A call for proposals will be announced annually in the early autumn. Project proposals can be made for one or several years. If funding is granted for a project planned to last longer than one year, it is likely to be also funded in the following years. However, the GMG may propose to the MEAE and VYR that funding is reduced from the original plan. In particular, the assessment considers whether the project has progressed as planned and whether changes in the operating environment have affected how effectively the project's goals can be met or the significance of the goals. The availability of VYR funding and the quality of the other proposals for the call also affect the amount of funding. Excellence projects will be funded according to the approved project plan and budget if essential changes in the plan have not been made (see section 2.2.1 for details).

The selection criteria for the project proposals to be funded include the project's ability to develop expertise, safety significance, novelty of the methods, new approaches, experimental facilities and networking in the field, for example. In particular, the implementation of the requirement of Chapter 7a of the Nuclear Energy Act will receive special attention. The requirement is to support the actors in the nuclear field and to ensure they have sufficient expertise and methods at their immediate disposal if it is necessary to assess the safety significance of new issues that may emerge.

The SGs in the SAFER2028 programme assess the project proposals, and the programme's MG will make an annual proposal to the MEAE on the research projects to be funded. The MEAE will make a proposal to VYR on one project entity that meets the requirements of the Nuclear Energy Act after consulting with STUK. The funding proposal for multi-year projects may differ from the plan proposed at the beginning of the project, as the emphases of the research programme's goals or the project's competitive situation may change. The selection procedure for research projects will be described in detail in the SAFER2028 operational management handbook.

During the project evaluation phase, the MG has the possibility to negotiate with the parties proposing projects and with the funders on changing the goals and funding, and on combining project proposals into larger entities. The MG will decide whether to include them in the project portfolio. A common criterion for all research projects within the programme is compliance with the Framework Plan.

When planning the projects and defining the funding share applied from VYR, the nature of the work to be carried out in the project should be taken into account. The project plan must consist of partial tasks aimed at a consistent goal and it must have clear interim goals, the attainment of which can be assessed during the project year and at its end.

Research institutions, organisations carrying out technological research and universities may receive VYR funding for up to 70% of the project's total expenses. For funding related to international participation fees, however, 100% VYR funding is possible.

Funding can also be granted to companies that are truly committed to the field of research. For these companies, 100% VYR funding is possible. Companies with 50 or fewer employees can report 50% of their indirect employee costs ('henkilösivukulut') and 30% of general overhead costs ('yleiskulut'). A company can also propose larger general overhead costs in reporting, but then it should be based on accounting. For bigger companies, the acceptable indirect employee and general overhead costs are 50% and 50%, respectively.

In addition, the de minimis rule of the EU state subsidy regulations will be applied to companies. If necessary, the EU Commission will be notified of the research programme by a decision of the MEAE.

2.3 Results of the research programme

The main purpose of the research programme is to promote the safe use of nuclear energy in Finland and to enhance the Finnish nuclear safety assessment capability for solving possible safety issues as they appear. This capability is assessed against the goal set in the Nuclear Energy Act, Section 53 a. The key areas to be assessed in the capability model are: 1) human resources and experts, 2) validated safety assessment tools, 3) nuclear safety research laboratories and research facilities, 4) career building, training and networking, 5) knowledge management and assets, and 6) general research programme indicators.

The goals for the SAFER2028 programme and beyond until 2034 are presented under nine topics. The overarching topics express more specific goals for the programme period. The list below presents the overarching research topics and their milestones for 2025 and 2028.

Table 1.1. The overarching research topics and their milestones for 2025 and 2028 of SAFER 2028.

Objective	Milestone 2025	Milestone 2028
Infrastructure capability	Infra SG evaluates and identifies possible development areas (roadmap) and reports to MG Preparation for fuel experiments transitioning to JHR on schedule Guidance on VYR-funded infra collaborative use in SAFER2028	Infra SG reviews progress of roadmap and reports to MG Preparation for fuel experiments transitioning to JHR on schedule
Overall safety and systemic approach to safety	Examples of methods and approaches presented Elements of the framework for evaluation of overall safety defined Examples of risk-informed graded approach in different safety management contexts presented	Methods and approaches that take the systemic nature of safety into account when safety is assessed and improved Framework for evaluation of overall safety Principles and practices for the application of risk-informed graded approach in different safety management contexts

Objective	Milestone 2025	Milestone 2028
Validated tools and methods for safety assessment	Further development of national computational tools, also taking the use of new applications into account Better, quantified understanding of uncertainties, how they propagate in analysis chains, and how they affect the applicability of tools in different application areas	New application areas in use Improved ways to manage uncertainties and expand applicability to new application areas
Nuclear fuel and its life cycle, from reactor to final disposal	New relevant research questions for SMRs and spent fuel management identified and projects started Research on applicability of accident-tolerant fuels	Understanding of the main features of relevant SMR spent fuel disposal concepts Research on damaged fuel rods in storage, encapsulation and final disposal
Ageing phenomena and the integrity of barriers of nuclear power plants	Identifying the most safety-relevant ageing phenomena with large uncertainties Ageing phenomena are covered in research projects	More comprehensive understanding of the ageing phenomena of safety-critical components and structures, state of the art Better interpretation of results (tests, NDT, monitoring, additive manufacturing, 3D printing, new concrete materials, …)
Long-term safety of final disposal	Roadmap based on competence mapping update Interactions of release barriers are covered in research projects	Operational and transient phase phenomena effects on long-term safety are included Safeguards perspectives are included in research Better understanding of uncertainties and adapting to changes
Safety and feasibility of short- and medium-term nuclear waste management activities	Surface repositories are considered in research projects Different waste streams from decommissioning are included in research projects	Alternative disposal concepts are covered in research projects

Objective	Milestone 2025	Milestone 2028
Severe accidents	Severe accidents in SMRs and consequences for acceptability and licensing are included in projects State-of-the-art analysis tools and understanding of phenomena are covered in research projects Accident progression in shut-down reactors and fuel storages are covered in research projects	Synthesis of different severe accident analysis tools are covered in research projects
External and internal hazards	Developing and maintaining sufficient understanding and assessment capabilities of seismic, meteorological and hydrological hazards, including the effects of climate change Capabilities for analytical or experimental qualification of structures and components for seismic events, aeroplane collision and explosions. The understanding and assessment of structural capacity scenarios on reinforced concrete structures is of great interest in terms of safety issues. Although experimental research on this topic already has a long and successful history, there are many issues to be solved as far as numerical simulations are concerned. The sensitivity of the simulation response with respect to model parameters will be solved. Methods and studies on multi-hazard analysis	Continued methodology development and maintenance of hazard estimates Incorporation of new methods in probabilistic risk assessment and uncertainty analysis
Nuclear safety in a changing environment	Produce relevant knowledge of SMR safety features, operation approaches and the implications for safety requirements Understanding effects of changing energy system on nuclear safety	In-depth understanding of new operation concepts and know-how on human factors engineering Improved understanding of how society perceives safety, risks and regulation needs in nuclear and other industries

The research programme is subject to international independent review in the middle and at the end of the programme period. With respect to the research programme's processes and structures, it is evaluated on the basis of internal audits and reviews. The annual MG review will assess the need for the development of the operating processes and decide on improvements to processes and structures.

2.4 Principles of publicity, rights and responsibilities

The instruments, machines, software and results obtained or developed in the research programme are the property of the performing organisation, unless otherwise agreed.

Decisions concerning the publicity of research results will be made between the contact person named in the funding agreement and the organisation responsible for the research. As a general rule, research results have to be publishable (Nuclear Energy Act, Section 53 d). Publications from the research programme will be collected annually for delivery in a suitable format for internal use by the organisations participating in the research programme. Export controls questions and other external policy questions must be addressed by the research organisations and the associated authorities should be contacted when necessary.

If the aim of a project is to develop new software, either entirely or mostly with VYR funding, the official bodies and other organisations taking part in the research programme have the right to use the named software according to specified terms. Charges for use of the software will be agreed on a case-by-case basis.

The organisation with the main responsibility for a research project is in charge of the completion and reporting of the research, in accordance with the agreement with VYR. The project manager of the organisation with the main responsibility is the contact person. The organisation with the main responsibility is responsible for the appropriate archiving of the research results in line with the operational management handbook. Funding terms attached to the orders define the invoicing schedule and conditions.

The administrative organisation and the programme director are responsible for the administration of the programme. The responsibilities of the administrative organisation are defined in the contract and the financing terms of the administrative project.

All VYR-funded projects shall provide their Finnish participants and the SAFER2028 organisations with access to the research results.

2.5 Communication on the research and information exchange

The research programme plays a significant role in educating new experts and in knowledge transfer. Learning takes place by participating in research work under the guidance of more experienced researchers. University theses are part of the reporting of the results. High-quality research, international collaboration, and novel connections with new areas of science and technology deepen and broaden the competence of more experienced researchers as well.

Attaining in-depth competence requires postgraduate studies and a doctoral thesis. The numbers of doctoral and other theses are important result indicators of the SAFER2028 programme. Postgraduate studies with scientific publications also increase the long-term nature and the scientific level of the research work.

Working as a member on the programme's MG, and in SGs and the TAGs is important for information exchange between research and end-user organisations. The research results will be spread among end-users and the end-users' needs to researchers. The programme's seminars and project-specific ad hoc meetings also serve as efficient channels for information exchange.

3 Doctoral Education Network

3.1 Background

Nuclear safety requires thorough knowledge, skills and competence in construction, operation, and decommissioning of nuclear facilities as well as nuclear waste management. The needs for competence in the nuclear energy field were assessed in report 'Report of the Committee for Nuclear Energy Competence in Finland'[5] as well as its update 'Survey of Competence in the Nuclear Energy Sector 2017–2018 in Finland'.[6] They show an increasing need for experts in nuclear safety and nuclear waste management in the years to come.

This kind of knowledge is obtained by education, particularly within doctoral studies that also provide tools and skills to deepen and extend knowledge. In 2012–2016, there was a national doctoral programme called YTERA (Doctoral Programme for Nuclear Engineering and Radiochemistry), funded by the Academy of Finland, the Ministry of Education and Culture, and other stakeholders. YTERA was successful, but it ended with a general change in education policy in Finland that transformed the funding model towards direct allocations to universities.

In the Nuclear Energy Research Strategy,[7] one of the key recommendations was to establish a national doctoral education network. Consequently, an overarching umbrella of doctoral education networks, run by universities or their faculties/schools, was planned after YTERA under name ENNUSTE (aka DEN-NST). In practice, however, it has not seen any activities due to the lack of funding and coordination.

In 2023, a Doctoral Education Network will be established to act as an integral part of the SAFER2028 research programme, with funding from the National Nuclear Waste Management Fund VYR. The organisation of the new network, strongly based on previous YTERA and ENNUSTE networks, is described in this chapter.

5 Publications of MEE, Energy and Climate, 14/2012, https://tem.fi/documents/1410877/3437250/Report+of+the+Committee+for+Nuclear+Energy+Competence+in+Finland+23052012.pdf

6 Publications of MEAE, 2019:22, https://julkaisut.valtioneuvosto.fi/handle/10024/161464

7 MEE Publications, Energy and Climate, 17/2014

3.2 Main features

The Doctoral Education Network under SAFER2028, dubbed DENSE, will invite all doctoral students in the nuclear energy field to participate, regardless of their home organisation and funding source. It has been estimated that there are over 100 doctoral students and some 40 professors at eight Finnish universities actively involved in relevant research fields. The SAFER2028 Framework Plan offers several multidisciplinary research challenges with opportunities in various types of doctoral studies. Networking is expected to enhance scientific cross-cutting discussions on nuclear safety and nuclear waste management as well as the multidisciplinary problem-solving capabilities of the students.

Doctoral students employed by universities are considered full-time doctoral students. Typically, universities request these doctoral students to finalise their thesis in a nominal four-year window, while part-time doctoral students, working at research organisations or companies, are not similarly restricted in time.

In Finland, many doctoral theses, especially those in chemistry, physics and technology, are carried out by part-time doctoral students. In the nuclear energy field, the role of VTT Technical Research Centre of Finland Ltd is traditionally strong. VTT and other research organisations like the Finnish Meteorological Institute (FMI) and the Radiation and Nuclear Safety Authority (STUK) collaborate closely with universities that supervise and finally accept the doctoral theses.

The funding of the Doctoral Education Network DENSE will be divided into operational funding, with a strong emphasis on networking and international collaboration, and direct salary funding. The former would be available to all doctoral students in the network, providing an additional motivation to engage with DENSE, while direct salary funding would be available only for a subset of full-time doctoral students, either as sole or partial funding, as well as a few part-time doctoral students for thesis finalisation projects. In a thesis finalisation project, a doctoral student moves to their home university for 4–6 months to concentrate on thesis work.

The operational funding is annually applied for in a DENSE coordination project. The operational funding will support targeted scientific activities, training and networking. These activities include, e.g.:

- Participation in conferences, workshops and summer schools
- Research publication-related costs
- Research exchanges and visits (mobility) of both short (1–2 weeks) and long duration (up to 6 months), including infrastructure use-related costs

- Networking events, such as annual seminars where students and members of the professional community meet and present.

It should be noted that the operational funding is to be allocated to the DENSE Steering Group in such a manner that they can be flexible in funding relevant activities. In practice, a project proposal with a budget is prepared by the consortium of universities and submitted to the annual SAFER2028 call.

In SAFER2028, salary funding for doctoral students is available as two alternatives: (a) salary funding for doctoral students within DENSE, employed primarily at universities as full-time doctoral students, and (b) project funding covering some part of the salaries of doctoral students participating in other SAFER2028 projects. The latter funding model has been used in previous KYT and SAFIR research programmes and will continue to be available in SAFER2028. It provides a functional funding mechanism especially for part-time doctoral students working in research organisations.

From the university and student perspective, option (a), which is new to SAFER2028, is preferable for full-time doctoral students. Many universities require funding decisions for at least two years (preferably for four years) when recruiting. This is especially true when recruiting doctoral students from abroad; here, long-term funding has to be secured. Additionally, doctoral studies should fit under a predefined topic that provides new scientific knowledge and may evolve according to progress.

In contrast, general research projects may vary in their focus from a narrow scope to the tackling of wider challenges, and from fundamental to application-oriented research. Therefore, in option (b), the entire project can seldom be used as such as a basis for a doctoral thesis. Type (b) funding also creates a great deal of uncertainty for the university and doctoral students. The Academy of Finland and philanthropic foundations are not ready sources of funding for applied research that is tied to the nuclear industry. As such, doctoral projects with type (b) funding can become untenable over time, leading to lost knowledge and manpower.

While project funding decisions in SAFER2028 are made for one year at a time, multi-year funding can be guaranteed for excellence projects (see Chapter 2). This same mechanism will be applicable for type (a) funding of doctoral students.

It is estimated that SAFER2028 can provide direct salary funding for 5–8 full-time doctoral students, but the level of funding may change in the future. Given the need for trained experts, we should be ambitious. It is also envisaged that this SAFER2028 funding may be the catalyst for additional funding for doctoral studies from other sources in the nuclear energy field.

3.3 Administration and funding decisions

Doctoral studies at universities, even if relevant to the nuclear energy field, are more fundamental in nature than SAFER2028 projects in general. Their practical applicability becomes clear in the longer term.

The Doctoral Education Network DENSE is administered by a dedicated Steering Group (SG-DENSE). In contrast to other SGs of SAFER2028, SG-DENSE also includes representatives from universities and research organisations and is chaired by a professor. In this manner, the SG can make sure that the scientific level (which is integral to the award of a PhD) of a project proposal is given a stronger emphasis in funding decisions than in SAFER2028 in general. SG-DENSE may consult external specialists if additional expertise is needed. The MG makes the funding decisions based on feedback from SG-DENSE.

In the evaluation process of doctoral project proposals, the following quality criteria (with precedence decreasing down the list) are applied, with possible updates later on:

1. Scientific level of the proposal
2. Relevance of project proposal for scientific goals of SAFER2028 programme (in the long term)
3. Recommendation letter from a supervising professor
4. Recommendation letter from a stakeholder organisation if applicable (industry, regulator)
5. International network connections
6. Overall participation of the host organisation in the wider SAFER2028 research programme
7. Complementary funding/in-kind funding already promised from other sources
8. Diversity of topics and disciplines within the Doctoral Education Network

It should be noted that applications for funding of doctoral studies may be written by an individual pursuing a doctoral degree or a research group wishing to hire a doctoral student. By default, the criteria above are also applied for thesis finalisation projects.

The actual project proposals (salary applications) are processed by SAFER2028 programme management among other proposals. However, processing operational funding applications as well as arranging the annual seminar may necessitate an additional coordinator to be nominated to support decision-making in SG-DENSE. The salary of the coordinator may be included in the collective project plan where the consortium of universities applies for operational funding, and the coordinator can be the project manager of this project.

While the term of SAFER2028 is six years, doctoral studies nominally take four years. Multi-year funding within one programme is possible for excellence projects, but additionally, funding decisions from one programme period to the next have to be possible in order to have a continuum of doctoral studies. This is difficult to ensure formally, but is agreed on a best-effort basis. In order to enhance this continuum from the beginning, SG-DENSE may decide to fund doctoral students who have already started their studies with other funding 1–3 years earlier.

It shall be emphasised that international networking is an essential element of doctoral studies. International connections can also be enhanced by SG-DENSE both in funding decisions and operational funding, like international mobility. International funding possibilities like those in EURATOM projects shall be advertised to all DENSE participants (see Chapter 4).

4 International Collaboration

4.1 Goals

The primary goal of international collaboration is to stay abreast of the newest and most significant research that serves the purposes of SAFER2028, and to convey the best and most advanced ideas, methods and results to serve the development of the domestic programme. Via participation in international forums, committees and research projects, SAFER2028 benefits from the latest international knowledge and obtains information on the results of the large international research projects. Via participation, the SAFER2028 community can also advance in international forum decisions and discussions that serve the purposes and views of the SAFER2028 programme.

The secondary goal of international collaboration is to increase/enhance the visibility of the SAFER2028 programme and its research achievements internationally.

4.2 Partners

The international organisations considered the most relevant to SAFER2028 include the International Atomic Energy Agency (IAEA), the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development (OECD/NEA), the European Atomic Energy Community (Euratom), the Sustainable Nuclear Energy Technology Platform (SNETP), the European Technical Safety Organisations Network (ETSON), SITEX_Network (Sustainable network for Independent Technical EXpertise on radioactive waste management), IGD-TP (Implementing Geological Disposal of radioactive waste Technology Platform) and the Nordic Nuclear Safety Research (NKS).

As regards bilateral cooperation between SAFER2028 and national research organisations, the most relevant countries are recognised to be France and the UK for Olkiluoto 3 EPR and Sweden for Olkiluoto 1 and 2 Asea-Atom BWRs. For the Loviisa 1 and 2 units, other VVER-440 technology users, such as the Czech Republic, Hungary and Slovakia are among possible cooperation partners. Considering nuclear waste disposal, countries such as Sweden, Czech Republic, Canada, Switzerland and Japan (to mention a few) are identified as potential partners in several projects as they are developing disposal concepts in crystalline bedrock. However, investigations and planning of disposal in sedimentary or salt formations can also offer opportunities or joint investigations and work.

The role of SMRs in SAFER2028 will affect the scope and extent of international collaboration as well.

4.3 International collaboration in reactor safety and nuclear waste management

In reactor safety research, Finland is a small actor in comparison to other countries, such as France, despite our tradition of unique national nuclear safety and nuclear waste management research programmes. Thus, there is a clear motivation and need to participate actively in international projects and committees.

In waste management research, Finland is a forerunner and many of the current international research issues have already been solved in Finland, where the focus is shifting to the implementation phase. International cooperation in nuclear waste management can benefit SAFER2028 and Finland when it includes topics other than technical implementation. The long-term safety aspects, Engineered Barrier Systems, uncertainty management and monitoring, present the focus of SAFER2028 on nuclear waste and its management, and these have also been identified in other countries as interesting research fields. In addition, the methodology development done outside of Finland can be considered useful to follow-up and also apply in Finland, when applicable.

4.4 Means and challenges of international collaboration

The means of collaboration include memberships in international organsations, their committees, working groups and other bodies, participation in international projects operating under these organisations, and bilateral collaboration based on bilateral agreements and respective forms extending from exchange of information to actual collaboration in a bilateral research project.

As regards the IAEA and OECD/NEA committees and research projects, MEAE decides on participation and the participating organisations, and nominates the representatives from Finland. In EURATOM and NKS, the projects are created based on a call for proposals followed by a selection process. The representatives in the projects and their decision-making bodies are nominated according to the respective project rules. As regards SNETP and ETSON, the eligible organisations decide on their participation and propose their candidates to the various bodies. In addition, SNETP and ETSON may have small internal research projects where the participants, and hence representatives in the project decision-making body, are selected among the project participants.

The current national and international legislation on data management does not allow registers to be maintained on persons on international committees or involved in projects within SAFER2028. Hence, information sharing on international collaboration needs to be carried out considering these restrictions.

As regards the IAEA and OECD/NEA committees and project, it is recommended that in the respective nomination the MEAE allocates the reporting duties to SAFER2028 (level, frequency, specific research area) and informs the SAFER2028 management. As regards all other committees and projects where the nominations take place by the participating organisations and where the activities fall in the domain addressed in SAFER2028, it is recommended that the respective organisation representatives inform the SAFER2028 management on such projects and/or committees and their willingness to report to SAFER2028 according to the publicity rules of the committee or project (level, frequency, specific research area). As regards bilateral cooperation, the communication is foreseen to be based on bilateral agreement between SAFER2028 and the other party.

In all cases the basic assumption is that the participating organisations cover their own costs in the international collaboration. The only foreseen exception is the case where based on recommendation by the SAFER2028 Management Group and the funding decision by VYR, VYR funding is used as a complementary funding source in a EURATOM project.

4.5 Collaboration with international organisations

Collaboration with the IAEA needs to be enhanced to better convey the information from the IAEA committees and working groups to SAFER2028 in order to get the best knowledge of the international needs, directions and trends for research planning. The research work done in SAFER2028 and in previous national programmes should be combined more effectively with the IAEA Coordinated Research Projects (CRP) and the information on these projects should be effectively conveyed to SAFER2028. A systematic approach and rules on having IAEA stipendiaries involved in the SAFER2028 research projects need to be decided by the SAFER2028 management.

As regards collaboration with the **OECD/NEA**, MEAE decides formally on Finland's participation in the joint research projects and nominates the members for the committees and working groups. The committees cover the major areas of the NEA's programme. NEA standing committees are comprised of member country experts who are both contributors to the programme of work and beneficiaries of its results. Exchange of information on the OECD/NEA projects and committee work should be enhanced in SAFER2028.

The OECD/NEA FIDES programme is a continuation of Halden's fuel programmes. It is planned to continue for 5+2 years, thus extending beyond the SAFER2028 period. FIDES consists of subprogrammes, called JEEPs (Joint ExpErimental Programmes). Many of the SAFER2028 projects are foreseen to have connections to FIDES. The challenge is how the information can be distributed within SAFER2028, as the distribution of research results is restricted for six years from the beginning of the project and the organisations that are allowed to receive the reports on results have been explicitly listed/named in the project agreement.

EURATOM's co-funded European partnership programmes (CEPs), previously known as joint programmes, will be the most important ones for SAFER2028. In nuclear waste management, EURAD is the ongoing joint programme and PREDIS is a sister project to EURAD. Presumably, EURAD will be followed by EURAD 2. In nuclear materials the ORIENT-NM project is planning a CEP. There is also a special topic on research infrastructures (NRT-12) that is very important to SAFER2028 and, if realised as applied, will include a significant project on road mapping. In addition, the EURATOM research projects initiated as a result of recent calls will overlap with the first years of SAFER2028.

As regards the joint programmes in nuclear waste management, the partners decide between themselves on the subject and funding. There are no public calls. The individual funding batches coming to the organisations are often relatively small compared to the previous model.

VYR funding is not expected to be used as complementary funding in EURATOM projects. However, in certain topics the connection between SAFER2028 and the EURATOM projects would be beneficial and for those cases there should be the possibility to use the VYR funding as the needed complementary funding and organise the reporting of the EURATOM project results to the SAFER2028 community according to the project's rules.

It is noted that the EERA Joint Nuclear Materials programme is concentrating strongly on GEN IV and fusion and is therefore not of primary interest to SAFER2028.

When possible, Finland and Sweden will act together in the Euratom research questions, thus ensuring better funding for Nordic projects.

The **Sustainable Nuclear Energy Technology Platform** (SNETP) is an R&D&I platform to support and promote the safe, reliable and efficient operation of Generation II, III and IV civil nuclear systems. SNETP is a legal entity, and NUGENIA, ESNII and NC2I operate under it. SNETP is the key player in European nuclear research and also involves the industry. The ENEN network and SNETP Working Group (WG) on Education, Training and Knowledge Management is particularly important to university student exchange and international collaboration. The SNETP is actively forwarding European research ideas towards the European Community (EC). Currently there is a strong interest in the SMRs in the SNETP.

It is important to activate the SAFER2028 member organisations that are members of SNETP/NUGENIA to have more representatives in the WGs, as these are bodies that largely define the SNETP's research needs and initiatives towards the EC.

ETSON, the European TSO organisation network, is strongly focused on the TSO work solely supporting the regulator via its strong founding members IRSN, GRS and BelV. As a network supporting and drafting regulatory research, it is important to SAFER2028. In particular, the expert groups (EGs) of ETSON are of prior relevance. SAFER2028 should obtain information on the relevant research and research initiatives and vice versa, to promote the research considered important in SAFER2028 in the European field for subjects in common with ETSON.

The **NKS** (Nordic Nuclear Safety Research) collaboration is important to SAFER2028 both in terms of reactor safety and waste management, in a similar way to how it has been important to the SAFIR and KYT programmes. Currently, VTT is a partner in almost all NKS-R projects and LUT is also participating in several projects.

SITEX_Network is a French non-profit association aiming to enhance and foster cooperation at the international level in order to achieve a high-quality expertise function in the field of safety of radioactive waste management, independent of organisations responsible for the implementation of waste management programmes and waste producers. The aim is to support the nuclear regulatory authorities and the civil society. SITEX_Network is open to any institution or individual party with an interest in the independent regulatory assessment of RWM activities. While ETSON in radwaste management is more interested in the front end (predisposal), SITEX operates at the back end (final disposal and long-term safety).

The Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) is dedicated to initiating and carrying out European strategic initiatives to facilitate the stepwise implementation of safe, deep geological disposal of spent fuel, high-level waste and other long-lived radioactive waste. It aims to address the remaining scientific, technological and social challenges, and support European waste management programmes.

EURADSCIENCE is a network of research organisations for radioactive waste management science within Europe. Its vision is 'To act as an independent, cross-disciplinary, inclusive network ensuring scientific excellence and credibility to radioactive waste management.'

4.6 Bilateral collaboration

Based on the CAMP and CSARP agreements with the US NRC, Finland receives the TRACE and MELCOR codes used in safety analyses. SAFER2028 should seek opportunities to widen the bilateral cooperation with the US NRC and the Canadian Nuclear Safety Commission, in particular in the area of SMRs.

France is seen as a major partner for bilateral cooperation. SAFER2028 should consider how the existing bilateral agreements of SAFER2028 member organisations with CEA and IRSN could be exploited as a step leading to cooperation at the programme level with these organisations. SAFER2028 should also consider cooperation with UK's new national programme. Sweden is a recommended bilateral partner beyond the NKS cooperation due to the long-term operation of the five Swedish NPP units.

4.7 Collaboration at the substance level

Sections 5.1–5.4 on research objectives define the most relevant international organisations, their committees and projects in their respective fields. The sections describe the current status and knowledge. During the SAFER2028 programme period, this operating environment is expected to change with ongoing projects completing their work and new ones arising.

In SAFER2028, similarly to the SAFIR2022 programme, there will be areas that are not specific for fission, such as human and organisational research and PRA/PSA. Cooperation and funding could also be sought from new sources like Nordforsk and the ITER programme.

5 Detailed Objectives of the SAFER2028 Research Programme

5.1 Overall safety and society

5.1.1 Description of the research area

The overall safety and society research field collects a wide range of nuclear safety research that overarches several topics, as well as topics affecting nuclear energy as a whole or that are present in several areas. Such topics include the concept of overall safety itself; safety and society; safety, security and safeguards interfaces; plant/facility-level issues; setting safety requirements and controlling plant design throughout the plant's lifetime; risk assessment; hazards; systems engineering; automation architecture; control room design and operations; organisational factors; and human factors.

The management of overall safety and the application of a graded approach to the safety issues arising at nuclear power plants are becoming increasingly important when preparing for the very long-term operation of existing nuclear power plants and nuclear waste facilities, and constructing new capacity that is planned for 60 years of operations. All in all, the practical implementation of a graded approach concept would benefit from a more holistic view of overall safety.

5.1.2 Objectives of the research

The main objectives of the research area in the SAFER2028 programme are to:

- facilitate the development of methods and approaches that take the systemic nature of safety into account when safety is assessed and improved
- further develop the framework for evaluation of overall safety
- improve understanding of how society perceives safety, risks and regulation needs in nuclear and other industries
- develop principles and practices for the application of risk-informed graded approach in different safety management contexts
- develop know-how on human factors engineering (HFE)

- improve capabilities of probabilistic risk assessment (PRA) and risk-informed decision-making
- ensure understanding of HOF (human and organisational factors) and HFE (human factors engineering) aspects in different application areas (e.g. in SMRs and in different life cycle stages)
- produce relevant knowledge of SMR safety features and the implications for safety requirements.

Due to its systemic and holistic nature, overall safety and society interacts with many other topics in the programme. The overlapping topics are partly described in this chapter, and partly in the following technically more specific research areas, as follows:

- Computational tools and methods that support overall safety assessment are mostly described in dedicated contexts in the following chapters.
- Uncertainty assessment approaches related to safety analyses for reactor safety, mechanical and structural safety, and spent fuel disposal safety applications are described in each chapter.
- Safety case methodology for the long-term safety assessment of spent fuel disposal is described in the Decommissioning, Treatment and Long-term Safety of Nuclear Waste section.
- Overall PRA research needs are described in this chapter but the Reactor Safety and Fuel Cycle area includes complementary topics.
- Seismic hazards analysis and fire hazard analyses are covered by the Mechanical and Structural Safety area.
- Human and organisational factors are mainly described in this chapter but they are relevant to all areas.
- I&C issues are discussed in this chapter, but are also relevant to other areas, in particular the Reactor Safety and Fuel Cycle area.
- SMR-related research is covered from various aspects in all research areas.

5.1.3 Research needs

5.1.3.1 Overall safety concept

The overall safety concept is an umbrella for safety thinking throughout the whole nuclear life cycle. Safety is a principal basis for all activities in nuclear energy and nuclear waste management and it is a prerequisite for societal acceptance of nuclear energy usage in society. In general, safety principles are rather well formed and they have been applied for a long time. In addition to that, the safety requirements given for licensees can be seen as transparent. It is, however, also important that everyone understands the requirements clearly and unanimously. Above all, there is a need to better understand the systemic nature of safety.

The overall good of society[8] establishes societal expectations for the use of nuclear energy, which is not usually addressed when setting safety requirements. The expectations and safety requirements also have financial effects, sustainability impacts and justice issues. The various impacts of expectations and safety requirements are often omitted in safety research, but they also affect the societal acceptability of nuclear energy through the top-level expectations of the overall good of society and practically possible solutions in maintaining safety, as well as the grading of safety requirements commensurate with risks (e.g. Nuclear Energy Act sections 5 & 7a). The expectations of society are related to the concept of overall safety, how safety in general is perceived, how risk is perceived, and how to proportion nuclear safety risks to other risks.

The balance of safety requirements that is asked for by having requirements commensurate with the risks usually takes into account the direct consequences of the operation and possible accidents. But including other expectations, e.g. societal values, that affect the concept of safety, may not be such an easy task. Still, these expectations lie underneath when evaluating the overall good of society, and thus they somehow affect the balance and the structure of the safety requirements. To achieve and maintain a good structure and a justified level of safety requirements, these underlying expectations should be understood adequately.

An overall safety evaluation tries to answer the needs above, but usually does this only partially. Therefore, understanding the different aspects and areas of safety needs to be further studied to better establish the concept of overall safety. Understanding safety from a wider perspective would help to evaluate more comprehensively how different sub-areas are linked to each other and how they affect the overall picture. There is a need to establish methods to evaluate and assess overall safety, and it is essential to recognise and understand the systemic nature of the whole. With a more comprehensive approach, the contribution of different areas and their importance to overall safety can be identified. Furthermore, through research we can also identify potential knowledge gaps and

8 The term "overall good of society" is used here as determined in Section 5 of the Nuclear Energy Act.

issues that should be further studied and also understand how different research areas contribute to and support the assessment of overall safety.

There are several approaches to overall safety, some of which have been studied and developed in previous SAFIR and KYT programmes. Safety analysis reports (SAR) are intended to comprise an overall safety view of a nuclear facility. Regarding nuclear waste management, a safety case is a corresponding overall safety representation concerning long-term safety. ISO 15288 'Systems and software engineering – System life cycle processes', a non-nuclear standard widely adopted in safety significant industries, provides a valuable background for overall safety. The overall safety assessment frameworks should be tested in practice. A fruitful approach could be to apply them in SMRs that may have a different safety concept to those in the current plant designs. The results may generate new ideas to develop the frameworks further and support improving the general safety approach and balanced safety requirements.

A safety case is essentially a tool to support decision-making, in particular the licensing process. In a decision-making situation, one must remember that the safety argument will be in competition with other arguments and therefore one must be able to process arguments from the safety case suitable for the particular discussion. In this respect it is a valuable opportunity to study how a safety case has been used in decision-making situations in different countries.

Even though safety cases are an established methodology, with perhaps differing national emphases, there is a need for continuous improvements. The stepwise decision-making system in Finland already requires the contents of a safety case to be improved from one step to the next. The NWM safety case has many common features with NPP safety analysis (see also section 5.3). Therefore, it is worthwhile analysing how the long-term safety factors are taken into account in the operational safety (or FSAR) and how organisational factors have been taken into account in the safety case methodology so far, and whether there are reasons to study organisational factors that could influence long-term safety.

Although the responsibility for nuclear safety is with the licensee, different organisations have their own roles in the overall process designed to ensure safety. Therefore, nuclear safety is affected by several different organisations, such as licensees, ministries, safety authorities, research organisations, vendors, non-governmental organisations, the public and the media (including social media). Understanding how this system of organisations works and how different organisations influence each other could help to balance out the different areas of overall safety and enhance organisational strength in depth and transparency. This would require more detailed modelling of the system of organisations to evaluate the systemic behaviour of complex networks in different situations. When studying overall safety from these perspectives, however, the explicit contribution to nuclear safety should be kept in focus.

Learning from experience from licensing first-of-a-kind (FOAK) facilities could provide valuable lessons for managing future nuclear facility projects, such as SMRs, spent fuel disposal, and decommissioning of NPPs. There are plenty of examples worldwide and also domestically in the nuclear field where due to technical, political and economical reasons, FOAK projects have, if not fully failed, at least have experienced serious hindrances. Analysing these experiences could help understand the reasons for the failures that could be possible in connection to the licensing of FOAK facilities, and help consider contingency plans in an early phase of such projects.

Nuclear safety, security and safeguards (the 3Ss) are closely related areas, and all have in common the aim of protecting human life, health and the environment. To meet this aim, nuclear safety, security and safeguarding measures have to be designed and implemented in an integrated manner, so that different measures do not compromise others. Safety-security-safeguards interfaces should thus be considered in the development of the overall safety concept, too. SMRs could be used as a case study, since if located closer to communities such facilities may bring about new security and safeguards concerns compared to existing nuclear facilities.

5.1.3.2 Safety and society

Design, planning, safety assessment and decision-making concerning nuclear facilities always take place within a specific regulatory context (framework), with its own socio-institutional characteristics and priorities. Not only do these characteristics differ across country contexts, regardless of common international guidelines, but they also change over time, thereby shaping the evolution of the regulatory regime in question. A nuclear safety regulatory regime can analytically be defined as consisting not only of the legal regulatory framework established by the authorities, but also including self-regulation by the industry, civil regulation (civic vigilance) by civil society (e.g. citizens, non-governmental organisations, potential host communities and media), and co-regulation of the above-mentioned parties and actors. The norms, perceptions and policies governing the relationship between the state and the market co-evolve with geopolitics, international trade policy, as well as lessons and experience from nuclear-sector projects. These changes in turn shape the perceptions concerning the need for and the nature of safety regulation.

Comparative studies across countries, industrial sectors and time periods help in understanding the dynamics of safety institutions and perceptions. Analysing regime changes helps to understand the interaction between the three elements of regulatory regimes (legal, self, and civic regulation) and the factors shaping those dynamics, in specific country-specific contexts and across different time periods. The relationships between these distinct forms of regulation, in turn, are crucial for citizens' trust in the regulatory regime – including the reliability, competence and sincerity of the key nuclear-sector actors (e.g. operators, safety authority, government, experts and civil society organisations).

Decisions about nuclear energy and nuclear waste management are based on accumulated scientific understanding from many years of high-quality scientific research. A second major contributing factor is long-term preparatory work undertaken by the whole nuclear community (legislation, regulation, funding, strategies, etc.). However, every decision is a specific political occasion that reflects wider societal perceptions of factors related to nuclear energy, such as safety. Therefore, it is necessary to understand which factors are the most crucial in any given decision-making situation. One way to help decision-making would be to compare risks related to nuclear energy production and nuclear waste management to those in other industries. The study should also review how requirements to manage different risks in different industries differ from those in the nuclear industry. The research topic could also review more widely what kinds of risks are societally acceptable and the related reasonings.

Analysis of risk and safety perceptions can also focus on specific societal target groups such as decision-makers, policy-makers, experts, journalists, or young people for whom a more detailed mapping of opinions, discourses and rhetoric is considered warranted. As society is constantly changing, research is also needed to understand how, for example, climate change, multiculturalism and social media affect safety perceptions.

One way to study risk acceptance is to analyse what approaches other industries have taken in an effort to improve their relations with the various publics, such as corporate social responsibility (CSR) and environmental, social & governance (ESG). The mining industry has adopted a concept called social licence to operate, which is essentially an instrument for companies and organisations to manage their social risks. Valuable lessons could be learnt from these experiences in non-nuclear sectors.

Societal priorities may change over time, and it may not be clear today what will be considered as major risks in the future. Will it be the radiological risks arising from nuclear energy generation or something quite different? SAFER2028 could utilise its multidisciplinary competencies to analyse what are considered major risks in society today, and explore possible future risks, for instance through scenario and foresight exercises.

The acceptability of nuclear energy is under discussion in a number of countries, as public support has decreased in some EU member states and increased in others, especially in response to growing climate concerns. These dynamics are reflected, for instance, in the ongoing discussion within the EU on whether investments in nuclear energy should enjoy favourable treatment as part of the EU's 'taxonomy' of sustainable investments. In Finland, public attitudes towards nuclear energy is currently relatively positive, as demonstrated for example by the fact that one new NPP is under construction and another is in preparation. It is important that there is understanding about the various reasons for anti- and pro-nuclear attitudes, e.g. what are the institutional structures and cultural factors that could explain differences in attitudes between countries?

In Finland, there are currently two new-build NPP projects, Olkiluoto 3 and Hanhikivi 1. Both have suffered from considerable delays, although they are at different stages of development, as Olkiluoto 3 is nearing completion and Hanhikivi 1 is in the construction licence application stage. The reasons for the delays could be studied from the point of view of the multicultural nature of the projects. The many international contractors and subcontractors come from various cultures, traditions and practices.

Another possible topic for multidisciplinary study is the SMR plans currently being prepared in many nuclear countries. As regards Finland, the possible SMRs would probably mean considerable socio-technical changes to the current nuclear energy production regime. The studies should ideally cover the whole life cycle of the facility, the entire nuclear fuel cycle, and the entire range of technical, institutional, economic and societal factors that affect the possible development of SMRs. Given that SMRs are only the most recent of a range of nuclear technology promises, multidisciplinary analysis of the factors likely to shape their development could usefully draw on past experiences and current developments of other nuclear technologies (e.g. fast breeder reactors, nuclear fusion, Generation III and III+, and Generation IV). Such research should acknowledge both the vital importance of bold promises and the dangers of conflated promises for the success of techno-scientific innovations.

The acceptability of nuclear energy depends logically on the acceptability of nuclear waste management (NWM), as NWM is the tail end of nuclear energy use, the whole of which must be managed in a responsible manner. In licensing nuclear reactors, it is indispensable that there is a feasible, safe and acceptable plan to manage all of the nuclear waste the reactor will generate in the future. The acceptability of NWM has been decreasing in many countries with the result of poor progress in national high-level radioactive waste management programmes. Although Finland is a world forerunner in NWM, it is important to understand the reasons for different situations, to know the strategies used in various countries to boost their NWM programmes, and to understand, in particular, why Finland is an outlier in this respect, and what that might imply for the future.

Nuclear waste management of SMRs may require a new approach as, unlike with current large reactors, the amount of waste produced per SMR is smaller and thus, a centralised NWM solution that would serve a number of parties under the waste management obligation would appear tempting. In addition, current nuclear facility licensees are large companies with the resources to handle their own NWM, something SMR owners may not have. The new approach will cover, for instance, regulation, licensing, siting and logistical matters.

5.1.3.3 Systems engineering

In this chapter, 'system' refers to system-of-interest, i.e. an entity as a point of interest. In the nuclear domain, this can mean the whole nuclear facility, or their parts, such as the emergency diesel generator system, or the fuel handling machine. Nuclear power plants and other nuclear facilities are complex systems that comprise a large collection of different technical components that co-evolve with humans and organisational factors. A systemic approach is needed in all life cycle phases to ensure safe, reliable and economical operation of the system.

Systems engineering is a broad concept rooted in the realisation that complex systems are constituted of a potentially huge number of interdependent components, whose interactions are so intricate that errors have unforeseen and potentially critical consequences. ISO/IEC/IEEE 15288 specifies systems engineering as a set of processes which use each other. These processes enable coordination across engineering disciplines and system stakeholders. The aim is to create a holistic and cooperative approach to engineering over the system life cycle.

However, ISO/IEC/IEEE 15288 does not describe a life cycle model. The life cycle model in use can depend on the system-of-interest, organisational aspects, etc. Also, the standard does not, in general, call for a model-based approach. Model-based systems engineering (MBSE) emphasises a more formal approach to system requirements, design, analysis, and verification & validation (V&V) across the entire life cycle. Digital models are needed for a wide array of topics, e.g. geometric and geographic models, requirement models, economic models, and models of human operational procedures. Using MBSE can help in repeating work and understanding the system itself.

Knowledge management in nuclear facilities is often based on organisational and thematic structures. Cybersecurity and commercial interests (including intellectual property rights) set up barriers for the sharing, co-use and automated analysis of design information. Digital models facilitate information exchange and improve precision. They facilitate tool support for V&V, failure analyses, PRA, and also operational phase activities like (runtime) monitoring, (predictive) maintenance or optimisation. A digital twin of a nuclear facility would facilitate complex prognostics. In any life cycle stage, advanced computerised approaches require the use of formal modelling languages, with well-defined syntax and semantics. In addition, one must manage research results as well as requirements. The knowledge management system must allow for agile entering of new data as well as the possible review of old data, among other things, in case new scientific expertise, or new requirements, were to make it necessary.

Human factors engineering (HFE) is a term used for taking human factors such as human characteristics into account in the design of a nuclear facility and its operations (human factors research is discussed in section 5.1.3.5). HFE has its own processes, some of which are joint or coupled with the processes of other engineering disciplines (e.g. I&C). Research is needed for a better understanding of how to carry out HFE activities in the context of different nuclear facility design and modification projects and how to better tie together HFE with systems engineering processes in order to improve the effectiveness of HFE. For instance, in different life cycle phases of a nuclear facility, HFE activities may take different forms due to the different operational goals of the phase. Similarly, HFE processes may be emphasised differently depending on the life cycle phase of the plant and the type of ongoing design. Current models of HFE in international literature do not thoroughly or strongly consider the nuclear facility life cycle. HFE research in the programme may use a different approach and identify the characteristics of an engineering project in which HFE is utilised in a timely and effective way. In this approach the life cycle issue shall also be addressed.

The technical systems that compose the overall system architecture need to be verified and validated; first on the system level, and then as the integrated architecture. During the design phase, the overall architecture keeps changing, so the analyses need to be constantly iterated. Re-evaluation might even be needed during the operational phases, after incidents or accidents. Justification of the overall architecture needs to address aspects such as safety, security, availability and efficiency. These aspects might lead to contradictory design requirements and the need to compromise between them.

Traditionally, in the design of nuclear facilities, their systems or plant modifications, the viewpoint of structures and components – the bottom-up approach – is highlighted. However, today, a top-down approach is also needed. Plant-level and functional aspects should be accounted for. Also, the safety design aspect has many approaches. In safety design, traditional initiating events are highlighted and safety systems are designed to mitigate them. Another approach is to redesign the plant totally or partly, and make sure that a certain risk (i.e. event) is practically excluded; that is, the behaviour or the structure of the system is changed. Of course, while a certain risk can be avoided, another one can then be enabled. Therefore, systems should be designed to be more resilient, in order to mitigate the propagation of failures. Resilience can be achieved in many ways, such as adding slack, adding safety margins, or adding more safety features (or means that can be used to achieve the same objective, and which are not dependent on each other). Which approach is best depends on the system-of-interest, what is the tolerated risk level, and other design targets. Thus, it should be understood that safety is built into the system. These aspects help not only the design of the facility, but also the safety assessment activities. New engineering and assessment methodologies should be designed and developed.

The safety margin concept is one of the cornerstones of the nuclear safety design and deterministic safety assessment (DSA). Although mainly applied to physical systems and their parameters, it could equally be applied to socio-technical systems. The safety margin concept is a robust approach to define safety requirements in the presence of uncertainties, but it has limitations in protecting the system only against one type of failure and not from other types. Safety margins may also be excessively protective. There is a need to refine and develop safety margins concepts to better serve the stringent safety requirements and potential safety threats to the facilities. This is particularly important for design extension conditions where available systems are sparse and the role of human actions is emphasised. The new safety margins concepts should allow the evaluation of human actions in exceptional situations and the unification of results from different safety analysis methods such as DSA, PRA and HFE.

Nuclear facilities are tightly coupled open systems, in which humans and organisational factors play a role. The facilities and their environment also interact. From a technical point of view, by adding components to the system, we make the system more complex but also add interactions, which tightens the coupling. Tight coupling means that small errors can propagate inside the system, and this may have repercussions external to the system. A technical failure can lead to organisational failures, and vice versa. Understanding the behaviour of the system, and how internal and external interfaces of system interact, is crucial. Also, it is good to remember that by knowing how the system behaves, and understanding what failure modes are, we eventually enhance the safety of the system.

The failure tolerance analysis is an integrated set of failure analyses chosen to demonstrate the acceptability of failure of safety functions. The aim of failure tolerance analysis is to show that systems performing safety functions and their support systems satisfy the failure criteria that are related to the defence-in-depth requirements. Failure tolerance analysis relies on the strong interplay of DSA and PRA, and possibly extending to HFE and Safety Engineering. There is a need to further develop the failure tolerance analysis methodology to be an integrated part of the systems engineering process for nuclear facilities and their systems.

The interconnectedness and complexity of the overall I&C architecture is a particular concern. In both Olkiluoto 3 and Hanhikivi 1 new-build projects, the design of the overall I&C architecture has been and remains a key challenge. Based on that experience, research into the overall I&C architectures of SMRs should be an early priority. Individual modular reactors as well as multi-module plants have I&C architectures different to Gen. III/III+ units, characterised by a greater degree of automation, the use of passive solutions, and overall, a different approach to defence-in-depth. Multi-module facilities in particular underline the need for a system-of-systems view to requirements, assessment and justification. Another new topic is the overall I&C design of the encapsulation plant.

For advanced V&V techniques like model checking, the design requirements need to be expressed formally. It is challenging to find common ground between representations that are understandable without specialist knowledge, and the proposed formal languages. One option would be to use natural language processing to derive machine-processable information from existing requirement specifications. Formal conceptual models (ontologies) also facilitate machine reasoning. It is possible that different techniques are needed to address both functional and non-functional requirements.

5.1.3.4 Risk assessment

The risk assessment research area covers a broad scope of risk assessment methods, practices and tools-related topics. A general aim is to promote risk-informed decision-making through better utilisation of probabilistic risk assessment (PRA) and also by better understanding the limitations of quantitative risk assessment. Many of the suggested risk assessment research topics can be connected to the graded approach safety management principle, where PRA should play a significant role. Although the graded approach can be regarded as an obvious principle to optimise the allocation of resources, its practical implementation is far from self-evident. Among other things, the challenges lie in the difficulty to unambiguously assess the safety importance of an item as well as in the variety of items, e.g. targets of the regulatory oversight, that are subject to grading. The scope of grading does not only cover structures, systems and components but also various safety-related activities, processes, documents, events, etc., during the whole life cycle of the nuclear facility. Principles and practices of a graded approach using PRA insights in various contexts should be studied. Comparisons of applications of a graded approach in other countries are encouraged.

PRA provides several risk metrics that can be used as measures to support the evaluation of overall safety, but the results need to be examined from different perspectives. The models and data behind these results are vast, and the presentation of the results, including uncertainties, require efficient tools to highlight and understand different aspects. Efficient and versatile result presentation tools support the use of PRA in design and operation and help in decision-making concerning risk balancing and the evaluation of the importance of operational events. Methods and tools to shorten the PRA development life cycle and promote high quality of PRA models and analyses, such as automating routine parts of PRA modelling and comparison of PRA models with actual plant design, would improve productivity and contribute to the credibility of analysis results.

PRA is a well-established method for the assessment of risks of nuclear power plants in the operational phase. In addition, PRA is required during the design and construction licence phase as well as the decommissioning phase. The requirement for the performance and use of PRA also includes spent nuclear fuel storages and encapsulation and final disposal facilities. Although the general approach for PRA is valid for all types of nuclear facilities and during different life cycle phases, each case has specific features to be taken into account. Method development can be required in the following contexts:

- PRA in the design stage. The challenges of a design-phase PRA include lack of detailed design information, lack of representative reliability data, and lack of supporting analysis to model new kinds of systems (e.g. passive safety systems). Research questions include requirements for a design-phase PRA, use of expert judgements methods to compensate for the lack of input data, and assessment of uncertainties related to lack of knowledge.
- PRA for SMRs. Risk metrics used for LWRs may not be fully applicable for non-LWR SMRs. Human reliability analysis may need to be adapted to cover new types of dependences and long mission times. Multi-module interactions can have both positive and negative impacts from a risk point of view, which should be taken into account in a PRA for a multi-module site. Consideration to locate SMRs closer to communities than current nuclear facilities creates a need for a probabilistic consequence assessment.
- PRA for the operation of spent nuclear fuel storages and final disposal facilities (long term safety assessment is discussed in section 5.3). Compared to nuclear power plants, the risks of these facilities are considered lower, e.g. due to long time windows in most of the relevant scenarios and due to a somewhat different inventory of nuclides. Simplified analyses could sometimes be justified, but the drawback of simplifications could be that risk information is biased when used to support risk-informed decision-making.
- Risk assessment for the decommissioning phase is a new requirement in Finland, and therefore the experience from such studies is limited thus far. Further studies to find reasonable and useful approaches may be needed.

In many cases, PRA modelling capabilities would be sufficient, but the applicable data is inadequate. These issues, however, cannot be simply introduced to PRA models on the basis of current understanding. Rather, from the PRA point of view, it should be formulated as to what kind of information is needed, and the understanding of the issue itself should be increased by specific research to answer this demand. Further method development and expertise as well as data analysis are needed in the following areas, for example:

- Human reliability analysis (HRA). Method development is needed for analysing human interactions that are not yet well covered, e.g. long time windows, multi-unit interactions, mobile systems and commission errors. Approaches to use HRA to support the HFE process should be developed. Possibilities to use more data, complementary to expert judgements, in the estimation of human error probabilities should be explored.
- Reliability analysis of digital I&C. Further method development to find practical approaches to model complex I&C systems is needed. Reliability data is mostly vendor- and system/equipment-specific. Reliability data studies and comparisons of approaches and reliability numbers would be useful.
- Reliability analysis of passive systems. New NPP designs include passive safety systems. The specific features of each solution mean that there is not necessarily any general approach to model passive systems. However, case studies can provide useful insights.
- Ageing analysis of systems, structures and components (SSC). Ageing means that constant failure rates assumed in PRA are not valid in the long term. The overall approach of using PRA for ageing management is needed, as well as SSC-specific case studies to demonstrate how data and operating experience are analysed to gain useful information for risk-informed decision-making.

There is a wide spectrum of internal and external hazards and their combinations that shall be taken into account in the deterministic design and PRA. Although the PRAs for current NPPs are quite complete with regard to hazards, the results also show that many hazards are important contributors to nuclear safety and there are large uncertainties in the assessments, both with regard to the frequency assessments and plant impact assessments. Methods for analysing and modelling different hazards for different NPPs vary, also internationally. Although the harmonisation of methods is not necessarily the primary target, consistency in various risk assessments should be a desirable objective. The review and comparison of methods used for different hazards and facilities would be important.

Research into hazards should include both overarching studies that aim at handling the completeness and consistency requirements of PRA and hazard-specific studies that aim at gaining a better understanding of particular issues. Regarding overarching studies, the relevant questions are:

- identification and screening of hazards (including their combinations)
- estimation of frequencies of rare events
- assessment of plant impacts, e.g. SSC fragilities or impacts on electric and I&C systems
- adjustments needed in HRA made for 'basic-PRA' to fit for hazards scenarios
- implementation of the multitude of hazards in the PRA model
- studies of cliff-edge effects.

Regarding specific studies, external hazards include issues where further research is necessary to maintain and improve the knowledge related to critical phenomena and their consequences. Some specific hazards, e.g. space weather-related phenomena, may require further studies to resolve their relevance for nuclear safety. Of special importance, especially for new units, is the influence of climate change and the resulting effects on extreme situations. Also, improved abilities to forecast incoming extreme weather phenomena, thus providing early warning and time for countermeasures, could have a substantial safety relevance. The scanning and exploration of such potential external hazards and factors affecting safety will need to rely on a range of different types of knowledge, including various disciplines but also non-academic expertise. Drawing on international experience and research, ways of integrating various types of expertise in the Finnish context need to be explored.

Since many external hazards are regional, the national expert organisations (e.g. the Finnish Meteorological Institute, Helsinki University Institute of Seismology) have an important role to play in collecting and analysing the measurement data. The SAFER2028 programme should be used as a forum to bring together experts from different organisations and in creating a national understanding of the external hazards in Finland. The work in the SAFIR programmes has helped the expert organisations to develop their know-how in this field, and this work needs to be continued in the new programme period. The expertise is also valuable in unexpected situations, as shown by the Fukushima accident.

It has been discussed that SMRs are safe enough to enable reduced emergency preparedness zones in the vicinity of the NPP. The possibility of an early release or a large radioactive release from SMRs creates a need for a probabilistic consequence assessment. Although level 3 PRA is not required in Finland, there can be a need to develop capabilities for environmental consequence analyses that can be linked to level 2 PRA in a proper manner. Furthermore, the model development and research on this topic could provide insights into the overall safety of operating NPPs and those under construction and design.

PRA has many potential outputs that can be useful for security and safeguards. These include the identification of a list of events due to malicious acts that might potentially lead to an unacceptable radiological consequence (URC) or a high radiological consequence (HRC), the identification of sabotage targets, vital areas identification, and an assessment of physical protection systems (PPS). Evidently, security and safeguards applications require modification of the models and complementary models, but the logic model of PRA can be directly used to identify critical failure combinations that should be prevented.

In the 2010s, STUK, together with the Finnish licensees, conducted a series of pilot analyses and projects to develop methods for the application of PRA in security analyses and design. The pilot studies demonstrated that PRA provides a useful methodology and tools for this purpose. Further development is needed to reach the full potential of PRA to support security and safeguards assessments. There can be practical limitations to the type of research that can be included in the SAFER2028 programme. Method and requirements development could be studied, and interface issues between 'security PRA' and 'safety PRA' could be resolved.

5.1.3.5 Human factors

Human activities throughout the nuclear facility life cycle are crucial for nuclear safety. Human factors engineering applies scientific knowledge about human factors to the design, modification or assessment of tools, machines and interfaces, procedures, work settings and jobs. HFE is discussed more in section 5.1.3.3 in the context of systems engineering.

Human factors research aims to create and improve the safe and productive operation of nuclear facilities. Human factors in the nuclear domain address many topics for personnel work such as competencies and their development, communication and collaboration among personnel, human interaction with technology, and human performance and cognitive processing in different plant situations. Human factors expertise in the nuclear domain are based on solid knowledge of the state-of-the-art research in behavioural sciences, as well as knowledge of the national safety regulations, international standards, and industrial needs and practices. Research in human factors has implications for topics such as HFE, event-based learning, human reliability analysis and organisational factors.

There are different theoretical and methodological approaches to investigating human factor topics that take different vantage points. Research is needed for improving the safety of operating and maintenance work. One relevant research approach is to focus on psychological processes in operating and maintenance work. More research is needed on the joint effects of workload, stress, fatigue, and situation awareness on operating work in different plant states, also including outage. Relevant research topics are related to the effects of task scheduling and multitasking on performance and the strategies that are used at the team level to manage workloads. There is also a need for better understanding of interrelationships between situation awareness and decision-making that can be used, for example, in the design of 'context-aware' decision support systems. This topic is also related to the development of effective operating procedures and personnel training.

Another approach is to focus on the work practices of operating and maintenance personnel and, for example, studying what role safety plays in individual behaviour and how operating and maintenance personnel weigh safety against other intrinsic goals of continuous operation of the facility. From the perspective of practice theory, in order to cope with the high complexity of the design and operation of nuclear facilities, there is a need for novel practices to support the demands of adaptability, flexibility and resilience that are based on a more proactive approach to consider the effects of human performance on nuclear safety.

There is a need to better understand the coupling between nuclear safety and security and different human activities such as operation, maintenance, inspections and testing. Both empirical and theoretical research is needed. The approaches of human factors research described above should also be used for studying and developing human work outside of the main control room and operating crew, e.g. maintenance work. A favourable solution is to develop a methodological toolkit comprising tools from different theoretical approaches in order to improve the dependability and effectiveness of human work in nuclear facilities and in their different life cycle phases.

Digital technologies provide unique opportunities for improving operational performance, enhancing the safety of nuclear facilities, and supporting the life extension of NPPs. With that aim in mind, there is a research need for a deeper understanding of how operators collaborate with automated complex systems and various kinds of autonomous agents. Research on human-automation collaboration focuses on the challenges and pitfalls related to various design approaches and interface solutions, such as human out-of-the-loop problems, trust issues, and misalignments between humans and machines. This is important as new plant concepts such as SMRs provide for higher levels of automation.

One solution to these challenges is to develop advanced operations support systems and human-system interfaces that are based on design philosophies, such as ecological interface design, but more research is needed on their impacts.

Extended reality technologies such as virtual and augmented reality have a lot of potential in the nuclear domain, allowing new forms of training and new ways to deliver information in the field, but their full potential has not yet been realised.

With increasing interest in small modular reactors, NPP flexibility and resilient NPP concepts, new control room solutions will be introduced that require changes in control room operations and work practices. Research on control room concepts is therefore needed. New plant types with a higher level of automation also engender new demands for maintenance personnel. Also, new life cycle phases such as ageing plants and decommissioning pose research needs for human factors research. Ageing plants require more frequent modernisations in which solid principles from a human factors point of view need to be developed. Since decommissioning differs from the normal operation state of the plant, human factors issues that have a potential impact on the success of a decommissioning project are apparently different. However, very little research has been undertaken thus far to identify those issues and develop tools for their management. Research on the safety implications of human activity in nuclear waste management and final disposal repositories is also needed.

There is a research need to study and develop a model of the characteristics and activities of an organisation that properly takes human factors into account in its operations. This research may lead to the development of a maturity model that describes how an organisation may develop from the early stages of consideration of human factors to a top-level vanguard. This research should take into account competencies and working processes, but first and foremost the working practices as indications of the human factors maturity of an organisation.

5.1.3.6 Organisational factors

Overall safety depends on the ability and willingness of key parties to give safety the attention it deserves in any situation. This requires a broad set of organisational capabilities, such as sufficient and competent human resources, mindful work practices, clear roles and processes, good leadership, safety-oriented decision-making, smooth human-technology interaction, questioning of the climate, functioning organisational structures, reliable contractor networks, and a shared belief that safety comes first. Human and organisational factors (HOF) affect all stages and all levels of safety-related decisions, technology development and implementation, the application of safety assessment methodologies, and any daily operative activities at the utility, supplier and regulator organisations in all life cycle stages.

Research on human and organisational factors has produced guidance, concepts and methods that can be used to develop and access either some of the above-mentioned topics, or the overall safety culture of the organisation. However, there is a need for further research on organisational factors in the nuclear energy domain due to the following reasons:

- Practical implementation of the organisational factors knowledge of the everyday work processes still needs improvement. Events and other deviations repeatedly reveal a need to pay more attention to HOF aspects in the nuclear industry. More applied, contextual, yet scientifically sound research is needed to support the application of the HOF knowledge in the Finnish context.
- Finnish nuclear organisations will, in the near future, face life cycle transitions (e.g. from design to construction, possibly from operations to decommissioning, and starting the operation of the final disposal facility for the spent nuclear fuel). The transition phases surface new organisational, cross-organisational and societal phenomena which need to be anticipated and managed. Life cycle transitions is an understudied organisational topic in safety science.
- SMRs bring up a multitude of human and organisational factors questions, e.g. what kind of roles, competencies, organisation and practices should be required from the licence holder? Who is the licence holder?
- Developing and maintaining the state-of-the-art human and organisational factors competence pool in Finland is largely dependent on relevant and ambitious research activities. Currently the pool of experts is very small, taking into account the extent of the HOF research area and the need to maintain independence between the regulator and the licence-holders.

Important research topics in the area of human and organisational factors include:

- Effective organisational event-based learning, especially from the HOF-perspective. Effective learning from events calls for identification of the underlying or root organisational and cultural causes of the events, and insightful formulation of corrective actions that address the sometimes deep, broad or even sensitive development needs. One international observation is that the number of root cause analyses in licensee organisations seems to be declining and corrective actions do not always grasp the underlying issues that should be solved. Finnish licensees have also identified repeating issues which indicate that the learning from the events should be further improved.

- Human and organisational factors in life cycle transitions. The transition from one life cycle stage to another (e.g. from design to construction, from construction to operations, and from operations to decommissioning) is a massive effort for a licensee organisation and its partners as well as the regulator. Simultaneous operation of the current life cycle stage and preparation for the new phase calls for resources, but also changes in the management system, competencies and culture. Novel HOF challenges, e.g. increased personnel turnover, may appear. Lessons learnt from other countries and organisations should be applied when designing for safe transition phases.
- Safety culture and leadership. The behaviour of managers at all levels of the organisation is known to be of great importance to safety culture. One of the questions related to leadership is how to create psychological safety and support a truly open climate in the organisation. Also, understanding how internationally recognised expectations for good nuclear leadership apply in the Finnish cultural context needs more research. Furthermore, organisational decision-making (e.g. operational, technical and strategic decision-making both at the organisational and individual level) is a key activity where the safety culture manifests, thus it should be carefully designed and assessed. Decision-making practices, priorities, powers, etc. typically attract substantial attention after an accident. Proactive consideration of decision-making in organisations would be beneficial for all parties.
- Organising for safety. Understanding how organisational structures influence safety is important. Licensees' internal oversight activities (including independent oversight) that monitor and assess safety performance become even more important, e.g. due to the strategic change of the Finnish nuclear regulator, which even more than before emphasises the licensees' responsibility for safety. The roles and models for organising internal oversight vary. The preconditions for an effective internal oversight should be better understood. This includes the processes and tools with which the licensee makes sense of its overall safety: how it continuously establishes the situational awareness, concludes its strengths and weaknesses, and decides on the development initiatives, including those that relate to leadership and safety culture.
- Human and organisational factors related to SMRs. Discussion concerning the SMRs have brought up questions related to organisational capabilities

and the regulations thereof. Practical questions include those such as: how to prepare for new organisations that have little or no nuclear expertise? What kind of roles, competencies, organisation and practices should be required of the licence holder, and what can be outsourced? How should the potential new business and organisational models be taken into account in the regulations?

- Human and organisational factor implications for the grid following operation.

5.1.3.7 International collaboration

International collaboration is relevant for all topics described above. Expected collaboration forums and means include:

- Collaboration with Euratom projects and the Joint Research Centre, as well as with US DOE National Laboratories (e.g. Idaho, Sandia, Brookhaven) in all topics.
- European Safety and Reliability Conference (ESRA) and the Society for Risk Analysis (SRA) and its regional organisations provide valuable contact networks for the whole scope of research in risk and reliability analysis.
- Comparison of societal acceptability of risks linked to nuclear energy, with risks linked to other industries in other countries. International collaboration could support better understanding of factors leading to different socio-institutional systems (e.g. political decision-making, regulatory framework).
- In the area of NWM, Finland is internationally an interest case for researchers and media. There is a need to better understand and explain which societal factors could explain the progress of such projects.
- In the area of systems engineering, relevant working groups or committees in IAEA, IEC, American Nuclear Society (ANS) and International Council on Systems Engineering (INCOSE) are worth noting. Nordic collaboration through NKS and Energiforsk should be pursued.
- OECD/NEA CNRA and CSNI working groups offer a wide range of topical studies and projects for regulators and their technical support organisations that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations. Some examples are presented below.
- In the area of PRA, participation working groups and workshops of IAEA related to PRA, safety and security, new reactor designs and SMRs; OECD/

NEA working groups, especially WGRISK and WGEV; ETSON expert groups especially on PSA and external hazards. Nordic collaboration, through NKS, Nordic PSA Group and Nationella Brandsäkerhetsgruppens projects, has traditionally been strong and should be pursued.

- In the area of human and organisational factors, participation in relevant working groups and workshops of IAEA, OECD/NEA working groups, especially WGHOF and Technical area 3 (Improved Nuclear Power Plant Operation) of NUGENIA. Nordic collaboration mainly through NKS. Nuclear power plant owners' group form networks where operational concepts and emergency operating procedures are developed.
- In the area of assessment of electrical systems of the NPPs, the OECD/NEA working group WGELEC provides a forum for the benchmarking of simulation tools and exchange of information of current safety topics.
- The overall safety concept could be tested, demonstrated and improved with SMR concepts in international projects.

5.2 Reactor safety and fuel cycle

5.2.1 Description of the research area

The research area of reactor safety and the fuel cycle focuses on experimental and computational analysis methods that are vital for the proper understanding of plant and fuel behaviour in situations that may challenge nuclear safety. The most relevant research questions concentrate on the fundamental safety aspects and on the understanding of the behaviour of core neutronics, nuclear fuel, plant processes and plant systems in both normal and abnormal situations. A basic requirement for all the activities related to reactor safety and the fuel cycle is the availability of sufficient expertise, analysis tools and research facilities required to handle the issues relevant today and in the future. Knowledge of possible hazards, both internal and external, that may threaten the safety of nuclear operations is a vital part of safety analysis. Specific research questions related to hazards are discussed further in sections 5.1 'Overall Safety and Society' and 5.4 'Mechanical and Structural Safety of NPPs'.

Most of the research in this area has traditionally focused on the safety of operating nuclear power plants. While that is expected to continue due to the high safety significance of operating nuclear reactors, the safety of nuclear power operations is not limited to that. Therefore, the research topics to be investigated are also expected to cover safety questions important for the storage, transport and final disposal of spent fuel and the safe operation of related nuclear facilities.

5.2.2 Objectives of the research

The main objectives of the research in the SAFER2028 programme are:

- To develop and maintain a comprehensive understanding of matters relevant for the safe operation of nuclear facilities. This includes understanding the phenomena, analysis tools and methods, related uncertainties, and nuclear technology covering both the facilities in use in Finland today and those foreseen in the future.
- To provide sophisticated and validated tools and methods for the safety assessments and licensing of both new units and modifications of existing units.
- To develop and maintain the research facilities and research expertise needed for the experimental work and for the validation of computational tools.
- To extend the use of analysis tools and facilities so that they can be applied to address safety questions relevant for the whole life cycle of nuclear fuel and facilities.
- To facilitate the upkeep and development of nuclear safety in a changing environment.

All work in the field of reactor safety and the fuel cycle should also consider possibilities for international collaboration, with the aim of taking advantage of the best available knowledge and facilities, the spread of information, training of new experts and increasing the utilisation of national research tools and facilities.

5.2.3 Research needs

5.2.3.1 Analysis tools and methods

Computational tools and methods are an essential part of demonstrating reactor safety. Reliable results from simulations of transients and accidents require well-validated tools and also experienced users of those tools. The validation of computational tools and methods should primarily be based on data from experimental facilities and measurements from events that have occurred in operating nuclear power plants. Comparison against simulation results obtained with established, already well-validated codes can be used for additional validation. Tools that are commonly used in demonstrating reactor safety are reasonably widely used and their validation is performed not only by code developers but also code users. New reactor technologies or the application of existing technologies to new designs might bring about new challenges to tools that are used in the demonstration of reactor safety. This can necessitate development of these tools or at least the validation of existing tools in new areas.

The validation of a computational tool or method should result in a quantified understanding of its reliability. In other words, all validation work should produce estimates of how large the error associated with the tool or method is, in some particular use and at some confidence level. Validation may aim for a conservative approach, in which the aim is to estimate the maximum possible error, or the best estimate approach, in which the aim is to estimate the error at some predefined confidence level (typically constructing the 95/95% tolerance limits).

The scope of applications for computational tools and methods can be further divided into a number of sub-topics, such as core- and plant-scale analyses, analyses of electrical systems, fire simulations, load and strength analyses, PRA, accident analyses, criticality safety and radiation shielding. Many of these applications have been covered in previous research programmes. There are, however, topics that fall between reactor safety and the final disposal of spent fuel that have been previously left beyond the scope of both SAFIR and KYT programmes. This includes in particular operations involved in the interim storage, transportation and encapsulation of spent fuel assemblies. Even though the applications are different, the tools and methods are largely the same as in the analyses performed for operating power plants.

New reactor concepts, in particular SMRs, bring new challenges for computational tools and methods. The specific features of these reactors (small core size, passive safety, unconventional operating conditions) should be considered by both code developers and users. Emphasis should be placed on LWR technology, but when applicable, the methods should not be limited to any particular reactor type.

There are several cross-cutting issues between these applications. The evaluation of overall safety requires core- and system-scale models for deterministic safety analyses. Deterministic analyses further provide source terms for PRA and accident analyses, as well as for the final disposal of spent fuel. With respect to the improvement of safety analysis capabilities, one potential research topic could be to further study the possibilities and benefits of some level of integration of tools and codes (e.g. Apros process simulator and FinPSA software). In any case, it is important to understand the relevant computational chains and the connections between the tools applied at different levels. Ideally, computational analyses should be accompanied by the associated uncertainties, which should be carried over to the next steps in the calculation chain. Even so, it should be kept in mind that the propagation of uncertainties is an extremely complicated topic, and the methods should not be chosen without considering their practical feasibility.

The development of computational tools has proven to be an efficient means of building national competence and educating a new generation of experts. Examples include the Apros process simulator, the Serpent Monte Carlo code, the FinPSA software, and more recently, the Kraken core physics framework. The further development and systematic validation of these and other similar tools should be encouraged.

In the field of nuclear thermal hydraulics, there is a continuous need for research and development related to tools and methods tailored at solving problems of vastly different scales. System-scale thermal-hydraulic codes are used for the analysis of nuclear power plants at the system scale, i.e. in scenarios where the overall behaviour of complete cooling systems have to be considered. While these tools, that are conventionally based on the one-dimensional description of flows, are highly approximative in nature, and are generally less accurate and reliable than codes more directly based on first physical principles, they remain the most important tool for deterministic safety analyses for the future.

While the presently available system codes have reached a mature state, multiple important issues remain to be investigated and enhanced. Among these are the employment of modern, fully implicit numerical algorithms, solving the hyperbolicity issue, more detailed modelling of the two-phase flow beyond the two-fluid flow model, more mechanistic formulation of constitutive laws, enhancing the capabilities with the modelling of three-dimensional flows, and continuous work with validation.

Subchannel codes are the conventional tools used for the thermal-hydraulic analysis of the nuclear reactor core. The main purpose of these codes is estimating safety margins, such as the departure of the nucleate boiling ratio. Subchannel codes can also be used in conjunction with neutronic codes to enhance the estimation of the fission power distribution inside the core.

Computational fluid dynamics (CFD) codes are generic simulation tools for the accurate simulation of three-dimensional fluid flows, the use of which has conventionally been limited to problems of fairly small size due to their computational complexity. However, CFD codes are increasingly used for thermal-hydraulic nuclear safety analyses, especially in situations where the accurate estimation of the three-dimensional flow field cannot be obtained by other means, such as by relying on one-dimensional system-scale codes.

While CFD codes can already be used for many of the same purposes as subchannel codes, subchannel codes will also play an important role in thermal-hydraulic safety analyses for years to come, especially when it comes to time-dependent two-phase flow analyses inside the core. The maturity of the CFD methods should be assessed by application, where they are useful already and where the benefits are so clear that further development work is justified. It should always be done before proposing research projects. One-phase CFD simulations are in many cases applicable to real life problems, while two-phase flow CFD is more in the development phase. In general, it is important to get the developed CFD methods into real use during the SAFER2028 programme.

For the validation of thermal-hydraulic models and methods, the existing data from experiments carried out in recent decades is still useful for many purposes. However, new data with more accurate, 'CFD-grade' instrumentation will also be needed for the development and validation of advanced thermal-hydraulic models and methods. This requires close cooperation between experimental and computational experts, and also both domestic experimental work as well as participating in international cooperation projects.

Thermal-hydraulic tools used for nuclear safety assessments should also have associated means for the quantification of uncertainties of simulation results. The uncertainty estimation may need some method development during the SAFER2028 programme.

The weight of risk insights, especially in the grading of safety issues and support for safety-related decision-making, has significantly increased in recent years. The availability of up-to-date PRA models, adequate presentation of underlying uncertainties and the sound verification and validation process are some of the prerequisites for enhancing the credibility of presented risk insights. Potential areas for further research could be methods and tools to shorten the PRA development life cycle and to promote high quality of PRA software, models and analyses.

5.2.3.2 Experimental research

The current Finnish experimental fuel cycle and thermal-hydraulic research is based on methods that do not require the use of radioactive materials. The main capability for research is located in the thermal hydraulics laboratory of LUT University, which has two integral test facilities and a number of smaller experimental setups for the research of individual phenomena, i.e. separate-effects test facilities.

The systems of the other existing experimental nuclear facility at VTT can be used for the study of reactor safety or fuel-related materials and aerosol science questions. In addition, they offer a limited opportunity for the study of active samples. However, full-length spent fuel rods cannot be handled at the facilities due to dimensional and radiation protection constraints.

The main purpose of all experimental facilities is the production of data that can be used for the development and validation of quantitative models. This means that the cooperation between experimental and computational research groups is very important for successful modelling. This cooperation needs to be extended to all phases of experimental work: design of facilities, planning of experiments and use of experimental data.

The current facilities allow the study of questions related to:

- Passive safety systems
- Development of modern measurement technologies
- Use of realistic process parameters, with some limitations (no current facility allows full EPR/VVER primary pressure to be utilised)
- Fresh and simulated fuel pellets and cladding
- Links to code validation
- SMRs (district heating)

One of the aims of the research programme is to preserve the capability of Finnish nuclear safety research to answer swiftly to situations that arise unexpectedly. This requires the maintenance of a material sciences laboratory and a thermal hydraulics laboratory. As the actual research questions that may arise are unknown, the most important feature of the facilities is their flexibility. Both major Finnish nuclear science laboratories should be maintained as viable research opportunities, which requires a certain expertise level among the personnel. Further, considering the resources and expertise, age structures within the research organisations must be considered. This involves the possible hiring and training of younger experts to also prepare for the inevitable future retirement of seasoned experts.

The thermal-hydraulic (PWR) PACTEL and PPOOLEX facilities are approaching the end of their useful lives and new approaches are needed either for their revitalisation or for the development of other facilities. The MOTEL facility is modular, but it was built especially with certain existing SMR types in mind. If other reactor types are to be obtained, this facility requires modifications. Possibilities for the utilisation of the MOTEL facility to study other reactor concepts than SMRs must also be considered. The facility was built to be modular and in a way for it to be possible to add more components and circuits if needed. Further, readiness and capability for building separate-effects test facilities for component-level and phenomenological studies must be maintained, and this is closely related to the above-mentioned swiftly arising experimental research needs.

Up to now, two Finnish organisations have published proposals for district heating reactors. If these reactor types are being developed commercially, questions related to them may arise, and most likely will require both integral facilities and setups devoted to specific phenomena. The financing for these needs to come from funding sources devoted to those projects, but some use of the SAFER2028 funds is foreseeable to support the readiness for nuclear safety evaluation. An integral facility devoted to such reactor types is preferable for the validation of safety analysis codes. This is particularly significant, because the flow regimes and thermal-hydraulic conditions inside a district heating reactor may be clearly different from those encountered in a conventional power reactor. This poses challenges both to fluid dynamics and material science. Some of the important specific phenomena to be studied also include the behaviour of solid rock as a heat sink and the behaviour of different pools used as heat sinks in the reactor concepts. However, the question of the magnitude of funding devoted to SMR research can only be determined during the course of the programme, as only such technologies that have a likelihood of being utilised should be supported by the programme.

In addition to SMRs and district heating reactors, one important and essential area in experimental research is passive safety systems. The building and utilisation of the PASI test facility in the LUT laboratory during the previous and ongoing SAFIR programmes was successful. The facility has proven to be very useful, and it has been used in various research projects to study the behaviour of a passive open-loop containment heat removal system. Experimental research of other types of passive safety systems must be considered for the SAFER2028 programme; these could include e.g. a passive heat removal system through steam generators, insulation debris filtering systems, or passive corium cooling systems.

Modern thermal-hydraulic measurement techniques have been successfully implemented and developed during the SAFIR research programmes, and it is foreseeable that the developing work must continue within SAFER2028. Some of the used techniques need upgrading, and the procurement of completely new techniques must also be considered. These could include tomography measurement devices, which have not been utilised in thermal-hydraulic research in Finland before, if needed. State-of-the-art modern measurement technologies have to be followed continuously, and this may lead to the procurement and testing of totally new kinds of measurement techniques.

5.2.3.3 Fuel

Maintaining nuclear fuel structural integrity during operation as well as in postulated accident conditions is a key safety issue. Relevant topics for fuel research include improving fuel reliability, performance, and safety during fuel operation, intermediate storage, and final disposal.

There is a drive for a more economic use of fuel, and in addition, the future electricity market demands the more flexible operation of reactors and fuel. Therefore, some specific topics of interest are the research of phenomena related to the burnup uprate and load follow operation of fuel. There are also new and emerging fuel technologies such as accident-tolerant fuel (ATF) and small modular reactor fuel that are of interest. ATF is interesting, especially for those technologies that improve both the reliability and the accident performance of fuel.

Participation in key international programmes and networks, such as the recently commenced FIDES (Framework for Irradiation Experiments), continues to be important to gain knowledge of the development and properties of new fuel pellet and cladding materials, including ATF. As before, most of the nuclear fuel-related experimental research will be performed outside of Finland. Nevertheless, a valuable Finnish contribution to international cladding and pellet material research can be made through full utilisation of the experimental capabilities at VTT.

District heat production with nuclear reactors has been widely discussed in Finland. Traditional LWR fuel materials and designs have been brought up as practical and available solutions for fuel technology. There is a long history of experiments and operational experience regarding these materials. However, the existing data is mostly from high-temperature, high-pressure conditions. The use of this data and experience for in-core operation in low-temperature, low-pressure conditions and possibly extended irradiation times needs to be justified through careful studies. The interesting phenomena include high fuel rod internal pressure relative to system pressure, the lack of thermal annealing regarding radiation damage, pellet-cladding interaction during power ramps, and so on.

Using mixed cores is a specific research topic with pressurised water reactors, where the open geometry of the cores sets challenges for demonstrating their safe and reliable operation. The need for mixed cores arises both from product development as well as from the use of independent fuel vendors. The differences in pressure-loss characteristics may drive stronger cross flows, and together with mechanical differences, these may reduce thermal margins and induce mechanical vibrations and thus impact fuel reliability and safety.

The safety of storage, transport and the final disposal of spent fuel needs to be demonstrated, in addition to the behaviour of the fuel elements in reactor conditions. The applicability and possible shortcomings of the present numerical modelling tools for nuclear fuel's interim storage and transport applications should be clarified, as this is a new research area between reactor use and final disposal. The new research questions could include radiation safety, radiolysis and hydrogen generation.

Spent nuclear fuel (SNF) is the most radioactive nuclear waste containing long-life radionuclides and therefore the knowledge of SNF characteristics is important. Burnup can have a significant impact on SNF characteristics and it is therefore important to study the effects of burnup uprates and lower burnups on SNF. Old or damaged fuel can have low burnup, as can district heating SMR assemblies. Low burnups are especially important in the case of fuel containing burnable absorbers. Understanding the performance of damaged fuel in Finnish conditions in different stages, such as interim storage, management, transport and final disposal, is also needed. The effect of accident-tolerant fuel (ATF) on SNF should be studied. Different irradiation conditions in different fuel cycles have an effect on SNF characteristics and should be further studied. District heating SMRs, for example, may utilise low pressure, low power and low burnup, the effects of which are not properly known. Other possible issues in different fuel cycles may include load following, different cycle lengths and proliferation risk, for example. Knowledge of uncertainties and their distributions can lead to enhanced safety and better-defined margins, yielding cost savings.

Criticality safety and burnup credit are important in several stages of the fuel cycle such as interim storage, transport and final disposal. Some topics of interest for fuel with burnable absorbers are burnup of the reactivity maximum, radial distribution of the burnable absorber, and reactivity coefficient k-effective (keff). Experimental data for partially depleted burnable absorber fuel is very limited. Therefore, uncertainties for all these factors are of interest. Criticality safety in the context of accident-tolerant fuel, burnup uprates, new burnable absorbers and SMR fuel at the front and back ends of the fuel cycle are also of interest.

5.2.3.4 Severe accidents

The target of severe accident research is to understand phenomena occurring during severe accidents and to be able to model these in a reasonable manner. There should be sufficient capabilities and know-how on modelling general severe accident progression and special topics that cannot be modelled sufficiently with integral codes. Experimental work on severe accident phenomena and systems is in many cases very time-consuming and expensive. Therefore, participation in international projects is often the only way to gain access to high-quality experimental data. Code development and the development of know-how is also typically part of experimental projects.

It is particularly important to have access to the Fukushima data. The chemical state of the corium at Fukushima could have a significant impact on understanding how corium can form different layers and what is important to consider in accident management strategies to cool the corium, either with the in-vessel or in ex-vessel core catcher. In addition to this, the knowledge from Fukushima can be used to assess code capability and other important issues.

There are notable uncertainties related to the behaviour of gases and steam, including combustion of hydrogen, inside containments and reactor and fuel buildings. Even though the use of CFD tools has been increasing, the majority of analyses are done using lumped parameter codes. It is important to have a proper validation base for both types of codes. Hydrogen combustion at the plant scale and relevant geometrical properties (e.g. piping) having an impact on combustion should be studied after small-scale experiments have been used for model development and validation.

Research questions related to the timing, characterisation and spread of radioactive releases are essential for the understanding of the accident consequences. Experimental work has been carried out at VTT and international facilities. Iodine is one of the most important nuclides in the short term, and caesium in long term. The behaviour of iodine has been studied quite extensively. However, work on an equivalent scale has not been performed with caesium, resulting in a lack of knowledge related to its behaviour. The impact of droplets formed by condensed steam on fission product distribution in the long term has not been considered in analyses and it would be worth studying.

Work in the past has been performed mainly for reactors in power state. However, the progression and management of severe accidents both in reactor shutdown state and in spent fuel storages are also relevant for safety research, especially due to the limited availability of systems intended for severe accident management, the possible deficiencies of the containment function and the large radioactive inventory of the spent fuel elements. For example, air ingression and its consequences should be considered.

The research topics presented above are also valid for SMRs. Discussions are ongoing regarding the possible locations of SMRs and even urban areas and placement underground have been considered, but suitable siting requirements and possible acceptability remain open. Experimental and analytical work on fission product dispersion in such an environment can bring new information and justifiable means to evaluate the acceptability of SMR technology, e.g. for the district heating of large communities.

5.2.4 International collaboration

Most, if not all, of the research questions listed above can benefit from international collaboration. In many cases it is a necessity. The descriptions above already named several research areas, including a follow-up of Fukushima activities, other severe accident experiments (like containment and fission product) and the FIDES programme, where international collaboration offers research opportunities that would otherwise not be possible within SAFER2028. The development and validation of thermal-hydraulic tools relies partly on international collaboration: experiments are performed on large integral test facilities, and the operation and maintenance of these requires lots of resources. Sharing these costs between an international group of organisations – e.g. within OECD/NEA or EU projects such as the currently ongoing OECD/NEA ETHARINUS – is beneficial to everybody. The OECD/NEA Committee on the Safety of Nuclear Installations (CSNI) and the Nuclear Science Committee (NSC) also have many other activities that are linked to Reactor Safety and Fuel Cycle of SAFER2028. For example, the Working Group on Analysis and Management of Accidents (WGAMA) of CSNI promotes the exchange of information and the development of codes and models used for safety analysis. Similar activities are ongoing within NSC for neutronic tools. Participation in the US NRC's CAMP programme on the other hand provides the Finnish nuclear community with access to codes such as TRACE and RELAP5. Finnish participation in the US NRC's CAMP programme will continue into the future. The SAFER2028 programme is thus expected to include a research project that will, as part of the project activities and costs, cover the in-kind contributions and fees of the US NRC's CAMP programme. The project proposals will be evaluated and funding decisions made based on the principles and criteria explained in section 2.2.

In addition to the many benefits listed above, international collaboration increases the visibility of the work done within SAFER2028, supports networking and may thus strengthen the fulfilment of the SAFER2028 objectives by expanding the user base and applicability of the tools and facilities being developed within the programme. Therefore, efforts to benefit from the strength of international collaboration are being encouraged within the SAFER2028 programme.

5.2.5 SMRs

Most SMR concepts rely on relatively conventional LWR technology, with innovative design features related to simplified system design and passive safety. Characteristic features include reduced core size, sometimes combined with natural coolant circulation and boron-free operation. These specific features should be understood and taken into account in the design and validation of computational tools.

Small core size results in higher neutron leakage, which emphasises the significance of the core outer boundary and the radial reflector. Computational methods applied in traditional LWR codes may not sufficiently capture the associated phenomena. A smaller number of fuel assemblies may result in core design challenges when one of the assemblies fails and must be replaced with a new one. Conventional operating procedures applied to a current large LWR may not be directly applicable to SMRs. Boron-free operation may pose new challenges to evaluation of safety margins and criticality safety during refuelling operations.

Natural convection poses challenges to both core- and plant-scale thermal hydraulics. The reactor operators have only limited control over the flow conditions in the primary circuit. The computational tools used for modelling coolant flow must be capable of handling the phenomena in different operating conditions, anticipated operational occurrences and accidents. Unusual flow and heat transfer conditions may occur, especially in district heating reactors, operating at low temperature and pressure. The specific challenges of natural circulation must also be taken into account in code validation.

From a safety analysis point of view, the passive safety systems that are typically at the heart of the nuclear safety architecture with SMR designs, can raise new questions and challenges for the probabilistic risk assessments (PRA). The estimated failure probabilities of active components and relatively short mission times, typically used in a plant-level PRA model, are not well suited for the analysis of the safety goals set for designs that offer long autonomy times and rely heavily on core cooling by natural circulation. The ways to implement such features and the related uncertainties in PRA modelling may require new ideas, new tools and new supporting experimental data.

5.2.6 Infrastructure

As explained in the section 'Experimental research' above, the availability of flexible research facilities with skilled personnel and modern measurement and monitoring equipment has served the Finnish nuclear safety research well in the past and is expected to do so in the future, as long as their operating requirements are taken care of. Finnish experimental nuclear research activities have mainly been concentrated at VTT and LUT University, each with their own strengths and specialities, and they are expected to play a major role in the upkeep and development of national research capabilities until the end of the SAFER2028 programme. Nonetheless, new research facilities and groups can also take part in SAFER2028 activities and support the build-up of national nuclear safety expertise. In addition to the facilities needed for experimental work, effective computing infrastructure with skilled personnel and availability of suitable codes is required for the modelling and analysis work.

5.3 Nuclear waste management, final disposal and decommissioning

5.3.1 Description of the research area

The Nuclear Energy Act (990/1987) requires that licence-holders whose activities lead to the creation of nuclear waste manage the waste they produce. Those responsible for nuclear waste management assume responsibility for the planning, implementation and costs of nuclear waste management. The planning of nuclear waste management mainly means research and development done for the purpose of nuclear waste management operations. In addition to the research and development programmes of the companies responsible for nuclear waste management in Finland, the act states that those responsible for nuclear waste management are required to participate in funding the national research programme. Thus, nuclear waste management is recognised as one of the central research areas in the national safety and waste management research programme SAFER2028.

The term 'nuclear waste management' is commonly used in Finland when referring to management of all waste streams generated by licence-holders. This includes the treatment, interim storage and final disposal of very low-level waste (VLLW), low-level waste (LLW), intermediate-level waste (ILW) and high-level waste (HLW). High-level waste is mainly referred to as spent fuel, as only small amounts of other types of HLW is generated in Finland. Internationally, the terms radioactive waste and spent fuel management are used more extensively instead of nuclear waste management.

5.3.2 Objectives of the research area

The objective of the research area is to promote the safe use of nuclear waste facilities and the development of solutions for the management of nuclear waste. The objective is also to ensure that adequate and comprehensive expertise and other skills are available to the authorities and those liable for VYR payments under waste management obligations. In addition, the goal of the research area is to support and complement the research programmes of the licensees under waste management obligations, and to further develop both national and international collaboration between the authorities, waste management organisations and researchers.

In SAFER2028, central topics within the research area of nuclear waste management are:

- Final disposal of low- and intermediate-level waste (LILW), including new materials arising from decommissioning activities.

- Total disposal system performance over the long term, and especially the interactions within and between the interfaces of bedrock, overburden, groundwater and engineered barrier systems (EBS).
- EBS, other structures and their combined performance; possible modifications and optimisation of the final disposal concepts arising from operational experience.
- Decontamination and minimising the generation of secondary waste during decommissioning, or pre-disposal treatment of radioactive waste in general.

5.3.3 Infrastructure

The national operating environment of the NWM research area is constantly evolving as the current nuclear facility projects follow their life cycles. The research area of decommissioning, treatment and long-term safety should also prepare for new technologies in upcoming reactor projects. New technologies may affect ways of implementing waste management methods and may lead to changes in disposal concepts. There is also a growing demand and interest in the international operating environment and market for nuclear waste management expertise developed in Finland, especially in the management of spent fuel. This may have a positive impact on the national operating environment, for example on the development and maintenance of national competencies.

Posiva's encapsulation and disposal facility of spent fuel is expected to enter into its operating phase based on KBS-3 disposal concept during this programme period. Before operation, Posiva will perform a trial run of the final disposal. The trial run consists of a full-scale disposal test with the final equipment under actual conditions. However, the canisters do not contain spent fuel in the test. The trial run is used to ensure that the work phases related to disposal operation proceed as planned. The trial run can also be used to demonstrate to the authorities and stakeholders that the processes and procedures related to disposal operations are in order. The start of operation requires the government's operational licence.

Nuclear waste management expertise is at a high level in Finland. The expertise is based on decades of experience of research, pre-disposal treatment and disposal of radioactive waste. Also, expertise gained from licensing the first deep geological repository for spent fuel (including research, site investigations, design and construction) is significant and out of the ordinary. Thus, Posiva and other national organisations provide tailored expert services within nuclear waste management. Teollisuuden Voima Oyj's Olkiluoto 3 plant unit will have its first operating years in the programme period. The plant unit will also start the use of the nuclear waste management systems established on Olkiluoto Island originally for Olkiluoto units 1 and 2. This means that the interim storage for spent fuel, interim storage for low- and intermediate-level waste, and the disposal facility for low- and intermediate-level waste (VLJ cave) situated at the plant site will be used for the handling, storage and disposal of operational waste from Olkiluoto 3.

Teollisuuden Voima Oyj's near-surface disposal facility for very low-level waste will be used in campaigns, and the first campaign is expected to take place in 2024. The potential use of a near-surface disposal facility will decrease the need for expansion of the VLJ cave, which may become topical in the 2070s for disposal of decommissioning waste from the nuclear power plant. Teollisuuden Voima Oyj is also preparing to include Posiva's very low-, low- and intermediate-level waste as a part of the nuclear waste management system established on Olkiluoto Island.

Fortum Power and Heat Oy is expected to decide on the extension of the operation or decommissioning of Loviisa nuclear power plant. If the operation of the power plant is extended, the total amount of spent fuel as well as low- and intermediate-level waste will increase, but the waste management methods remain primarily the same as those currently used. If the operation of Loviisa power plant is not extended, it will decommissioned after the current licensing period. Decommissioning begins with a dismantling preparation phase that lasts for a few years and starts within this research programme period.

The operating licence for the low- and intermediate-level waste disposal facility in Loviisa is valid until the end of 2055, but operation of the disposal facility needs to be extended and facility to be expanded for the disposal of decommissioning waste. Fortum has applied for an extension of the LILW repository licence until the end of 2090. The licence might be the first operating licence for a waste disposal facility in Finland to include the disposal of decommissioning waste of a nuclear power plant.

The FiR 1 research reactor at VTT was shut down permanently in 2015. The government granted an operating licence for the decommissioning and dismantling of the research facility in 2021 after the spent fuel of the research reactor was transported to the United States for further use. VTT has an agreement with Fortum Power and Heat Oy for the decommissioning and dismantling of the research reactor, as well as storage and disposal of low- and intermediate-level waste from the research reactor in the Loviisa nuclear power plant area.

During this programme period, VTT is expected to move on to the execution phase of the decommissioning and be able to complete the decommissioning of the first nuclear facility in Finland. Before the execution, VTT continues to prepare for decommissioning and dismantling, for example by verifying calculated estimates of radioactive materials by means of sampling and measurements. In addition, decommissioning of the material research facilities at Otakaari 3 is ongoing at VTT.

The Hanhikivi 1 nuclear power plant is expected to enter the construction stage during this programme period. In addition to the nuclear power plant unit, the facilities being built consist of nuclear facilities that are used for the storage of fresh nuclear fuel, interim storage of spent fuel, and for the handling and storage of low- and intermediate-level nuclear waste. Fennovoima is applying for a construction licence for a disposal facility for low- and intermediate-level waste separately. In connection with the disposal of spent fuel, Fennovoima is expected to continue negotiations about extended nuclear waste management cooperation with the parties under waste management obligation. At the same time, Fennovoima will go ahead with its own disposal planning and development.

In 2017, the Ministry of Economic Affairs and Employment appointed a working group (known as the YETI group) to explore the objectives, development measures and alternative solutions for safe and cost-efficient nuclear and radioactive waste management. The authorities, universities and licence-holders were represented on the working group. Based on its work, in 2019 the working group issued an opinion about the target state of the nuclear and radioactive waste management and recommendations for reaching these targets.[9] It was the working group's opinion that it is important to ensure appropriate management of all existing and future nuclear and radioactive waste regardless of its origin, producer or production method. Finland must have in place procedures that cover the processing, storage and disposal of all nuclear and radioactive waste originating from Finland. It was further deemed expedient to primarily use existing infrastructure to implement low- and intermediate-level waste processing and disposal. This will require the cooperation and development of the nuclear facilities' licence procedures. From the licence holder's perspective, cooperation is feasible if it does not affect companies' electricity production or the sociological acceptability of operations. During this programme period, these cooperation measures could be taken into account.

Finland is developing nuclear and radioactive waste management in accordance with the international legislation. The national programme, which covers the national nuclear waste management programme[10] and the national radioactive waste management

9 Final Report on the National Cooperation Group on Nuclear Waste Management; MEAE, 2019:45. https://julkaisut.valtioneuvosto.fi/handle/10024/161763

10 Nuclear Energy Act, section 27b

programme,[11] was initially prepared for the EU Commission in 2015.[12] The second programme was completed in 2022,[13] and it included several development objectives for the coming years. Finnish nuclear and radioactive waste management has also been reported in the seventh national report delivered to the IAEA.[14] Finland's nuclear and radioactive waste management programme will be evaluated by peers as an IAEA´s ARTEMIS mission in 2022.

The SAFER2028 research programme also supports the development of research infrastructure. The VTT Centre for Nuclear Safety, which was partly funded by earlier research programmes, was completed in 2016. The Centre for Nuclear Safety has laboratory facilities for nuclear waste research, and the facilities are easily accessible to other researchers in the research area.

5.3.4 SMR

The most advanced concepts of SMRs are light water reactors and, in that sense, relatively traditional reactors. Therefore, the waste generated during operation and decommissioning is similar to the existing reactors and final disposal of LWR SMR waste generally follows the same principles and conventions. However, due to the size and modular structure, there are some new aspects that should be studied, such as the handling, transportation and encapsulation of smaller fuel assemblies.

The new aspects may be related to the volumes of LILW and possible new types of waste generated from SMRs. District heating and other decentralised applications of SMRs may require a revisiting of the practices applied to the back-end of the fuel cycle. Due to differences in the reactor sizes, the fuel assemblies are smaller, and in some cases, may have higher enrichment. These are issues that needs to be taken into account in final disposal planning. Since the SMRs are new types of power plants, relying mainly on passive safety systems, the volume of operational and decommissioning waste may vary. The decommissioning methods may differ from those of conventional large NPPs,

11 Radiation Act, section 87

12 MEAE 2015

13 MEAE2022; Management of spent nuclear fuel and radioactive waste in Finland: Second national programme under Article 12 of Directive 2011/70/EURATOM of the Council of the European Union, https://julkaisut.valtioneuvosto.fi/handle/10024/163877

14 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. 7th Finnish National Report as referred to in Article 32 of the Convention. STUK-B 259, Helsinki 2020, 157 p.

and should be done in international cooperation since there are no actual experiences anywhere in the world.

SAFER2028 research on SMRs is focused on light water SMRs. More advanced types of reactors may be studied if there is a need for the information among the companies planning to build such reactors in Finland.

5.3.5 Research needs

5.3.5.1 Predisposal of radioactive waste

Radioactive waste generated at nuclear facilities during operation and decommissioning contains waste streams with activity concentrations ranging from very low level to intermediate level. The generated waste streams are handled, contained and packed at the nuclear facility in accordance with the waste acceptance criteria set by the disposal concept. In Finland, low- and intermediate-level waste is geologically disposed of into bedrock repositories. Very low-level waste can be disposed of in the bedrock or in near-surface disposal facilities. Due to this, it is essential to understand the behaviour of the waste itself, the waste containers and the technical structures in disposal conditions.

The main principle of nuclear waste management is to minimise the generation of radioactive waste. Thus, there is also an interest in developing the handling and packing methods for both operational and decommissioning waste to reduce the amount of waste to be disposed of. Clearance of waste from regulatory control is also related to the reduction of the waste volume. New technical solutions for the solidification of liquid radioactive waste, with better long-term durability features in the disposal environment, is identified as a topic of interest within radioactive waste treatment.

There may arise new materials to be disposed of during the decommissioning of nuclear facilities that have not been licensed by the parties under waste management obligation. The development of handling and packing methods of these waste streams is seen as a useful research topic.

5.3.5.2 Nuclear waste disposal and long-term safety

Siting and site characterisation

In Finland, there is much experience of the siting process and site characterisation for spent fuel and LILW repositories. Emerging new technologies such as SMRs may set new needs for the siting and site characterisation, considering both SMR siting and possible SMR waste disposal facility siting. This is especially the case if new disposal methods are considered (e.g. deep bore hole disposal, see section 5.3.5). Even with the current selected sites in Finland uncertainties still prevail with several topics, and the understanding of them should be increased.

For site understanding of all disposal methods, there are many aspects that can be improved to reduce uncertainties in the overall site understanding. These include the development of methods for predictive studies on the host rock properties (e.g. seismic/aseismic processes).

Mechanical stability predictions of the host rock require an understanding of existing geological structural systems, brittle tectonic history, and the risks of geologically imminent seismic activity (e.g. 1 million years). For southern Finland, the current understanding of the detailed brittle tectonic history is mainly based on work connected to site investigations at Olkiluoto and from a couple of case studies.

Deep groundwater systems and deep biosphere (i.e. microbiology and fungi) show significant variability between the locality studies so far in Finland. These differences are related to the above-mentioned geological factors as well as the overall dynamics of the hydrogeological system. There have been recent developments in this field of research, but several lesser studied topics remain, such as processes related to gases in the bedrock and microbial processes in different geological environments. Groundwater systems are dynamic, partly due to construction-induced changes, and hence they act as a driving force for potential detrimental processes related to nuclear waste disposal. In recent years, the focus has been on Olkiluoto, but similar phenomena are of relevance to other concepts and sites as well.

Safety assessments need validated groundwater system modelling tools, and despite continuous development of hydrogeological models, further work is needed for model development and model validation. Specifically, there is a need for better modelling tools that can handle all relevant hydrobiochemical processes.

Hydrogeological and hydrogeochemical short- and long-term evolution are included in the SAFER2028 research programme, with a specific focus on deep geosphere (e.g. gas contents in groundwater and microbial processes), less studied phenomena, novel methods and topics linking the structural geology and microbiological factors. Reference studies and natural analogues for the site investigations at Olkiluoto are important for addressing and reducing uncertainties on the overall site understanding and knowledge.

There are new and more efficient data collection methods available for site characterisation activities resulting in vast amounts of data. Due to larger databases, new processing methods and tools (e.g. machine learning, AI-assisted analyses) and work-flows for 'big data' must be developed.

The individual components and their performance in current disposal concepts for SNF and LILW have been studied extensively in recent years. However, the disposal concept is a complex environment where several EBS components will or might interact with each other. To reduce uncertainties in EBS performance, more knowledge is needed about component interaction with each other or with environmental factors. One unpredicted environmental factor might be microbiological mechanisms arising from the surrounding environment (i.e. groundwater) or from EBS materials (i.e. backfill or buffer materials). Also, topics concerning possible hydrogeochemical evolution during the operational phase and in the long term are included in SAFER2028 programme.

Geological disposal facility design, performance and monitoring and optimisation

The performance of the KBS-3-type repository relies very much on the engineered barrier system (EBS) consisting of copper canisters, bentonite buffers and tunnel backfills. The overall performance of EBS at the Olkiluoto disposal facility has been much investigated in recent years, especially regarding the EBS components and the bedrock of the SNF repository. However, investigations should continue with several topics due to the high importance of EBS with regard to long-term safety. This is true also for cement-based barriers in LILW repositories.

As a new topic, the imminent starting of operations of nuclear facilities sets requirements on production and quality control, where new technology/new applications of existing technology could provide useful methods (for example non-destructive methods).

Optimisation of the disposal facility design and consideration of alternative materials may arise from changes in the global market or new innovations. To date, much of the data used in EBS performance assessment is based on the few well-characterised materials. For well-known materials, the understanding of single component performance is in a satisfactory state, but studies focusing on either alternative materials or the combined performance of the EBS (and/or host rock) are included in the programme. All this requires systematic experimental programmes, which also combine several materials in the same study in varying conditions, e.g. copper-bentonite, bentonite-bedrock and backfill-bedrock.

The post-closure safety and evaluation of fulfilling safety functions rely heavily on different modelling methods and tools. Modelling and the related data, including chemistry, form an important method for studying the EBS. All modelling should be based on reliable and consistent data, which is often hard to produce – and difficult to publish as such. The EBS is composed of many components and conditions (like groundwater composition and temperature) and their gradients are expected to vary. The uncertainty and sensitivity of the whole system on all these variations has not extensively been studied yet and thereby, interactions between the EBS materials under disposal loads is one of the key issues.

Monitoring of the disposal facilities during operation and post-closure is heavily dependent on the development of new monitoring methods, especially when monitoring is done without sensors in parts of the closed facility.

In addition to near-field EBS, closure materials, methods and joint performance with other technical structures, and potential alternatives for current closure materials are recognised as fields that would benefit from additional and innovative research projects. In addition, alternative disposal concepts (see section 5.3.5) can provoke needs to investigate new materials.

5.3.5.3 Long-term safety aspects and safety case methodology

Performance and safety assessment

Safety case formulation and its fundamental parts, i.e. safety functions, performance targets, performance assessment, scenario formulation and safety assessment are of great interest to the programme. Safety case methodology education will also still be needed in the future.

Performance assessment is a way to assess repository behaviour during the operational phase, in the transient phase soon after closure (in the short term), and in the long term. After the closure of the disposal facility, there will simultaneously be multiple kinds of individual or coupled transient phase phenomena: chemical-, rock mechanical-, hydrological-, thermal-, biological- and radiation-related. The most intense transient phase will be over in a few thousand years, when the potential heat generation has significantly decreased, but it could cause partly irreversible changes to the multibarrier system. These irreversible changes can lead to weakened safety functions. Detailed research on the transient phase and its effect mechanisms requires simultaneous coordinated interdisciplinary analyses of many fields. In addition, a potential criticality hazard of SF is of concern both in the short and the long term.

Despite the radioactive decay, high-level waste remains hazardous for a very long time because of its radioactivity and chemical toxicity, although radiotoxicity will reach the same level as natural uranium in about one million years. Various climate- and tectonics-driven processes can cause disturbance to the (SF) repository systems in the long term (changes in host rock properties including groundwater). During very long time spans (up to one million years and beyond) the probability of all of these phenomena being detrimental to the containment and the isolation of the repository increases because of the various climate-driven processes (bedrock erosion due to moving glaciers). Very long time spans of the performance assessment rely heavily on the conceptual understanding derived from geological sciences. For some of the key materials and processes for spent fuel disposal, there is a sound basis from the natural sciences. However, gaps exist and many waste management organisations internationally still seek information on the topics previously based on qualitative references with new research projects that target the delivery of more quantitative data or more details in conceptual understanding. For many specific processes, the available information on long-term behaviour is still sparse and for some alternative or new materials it is non-existent (including the waste). Furthermore, analogue-based studies have traditionally focused on the conditions at (SF) repository depth, but a similar approach could be applied to disposal facility system parts closer to the surface (e.g. closure materials) or other repository concepts. Research in the future should aim to increase the knowledge to cover the materials not previously studied, obtain new data to help reduce uncertainties and/or significantly improve conceptual models.

Safety assessment also deals with the radiological safety consequences of disposal involving the source term, migration in the near field, the far field and in the biosphere, and the dose assessment in various formulated scenarios. Safety assessment methodology development can involve the improved treatment of uncertainties in all these areas.

A special topic is C-14, which is a significant radionuclide in operating waste, spent fuel and decommissioning waste. Despite long studies, there are still uncertainties about its speciation. The uncertainties are handled as conservative assumptions in safety assessments regarding the chemical behaviour of C-14. Carbon is also fundamental to organic matter and its behaviour in the biosphere has proven to be difficult to model. There are persistent uncertainties in the biosphere behaviour of C-14 and its dose assessment modelling.

Post-closure safety case and uncertainty management

This scenario refers to an evolution scheme describing the potential future behaviour of the disposal system. The formulation of scenarios is a fundamental part of a safety case on which the safety assessment can be based. A fundamental problem in the long-term safety case is to prepare for the unpredictable future, which requires the management of uncertainty at its deepest level. Performance assessment, formulation of scenarios, safety assessment and sensitivity analysis form a fundamental part of the overall uncertainty management of the final disposal. Development of sensitivity and uncertainty management tools and skills will be an important part of future education. These can involve mathematical and anticipation tools, alternative models, or any other method that can be found from various other scientific areas and can be applied to assessing uncertainties of the final disposal.

SAFER2028 welcomes research project proposals related to the development of uncertainty management and future anticipation methodology, or methods that could possibly challenge the current ways of scenario formulation methodology in the field of disposal.

Near-surface disposal facilities

Near-surface disposal facilities have previously been used for hazardous waste and low-to-intermediate–level nuclear waste in other countries (e.g. UK, France). Similar facilities are planned for Finland for very-low level waste, but further research is needed on the design, performance and monitoring aspects that will be required for a Finnish near-surface disposal facility. In particular, issues concerning waste evolution and effective containment (limited transport) through engineered barriers and into the geosphere needs better parameterisation (e.g. biochemical reactions, colloid formation and transport), as do possible climate-induced changes (e.g. increased precipitation, sea-level rise) that could potentially lead to changes to the stability of structures and local hydrogeological conditions. The need for and the type of monitoring needed for such facilities during operation and post-closure also needs to be properly defined.

Disposal of LILW

LILW disposal concepts include various materials in the constructed structures, waste packages and the waste itself. LILW to be disposed of includes radioactive waste generated during operation and decommissioning phases. It is important to understand the evolution and potential interactions of these materials during the repository timescale. Additionally, the surrounding bedrock and groundwater are intrinsic parts of the disposal concepts (see also above regarding climate change that could potentially affect LILW repositories).

In geological LILW repositories, the evolution of waste material itself may affect the performance of the repository. Examples of the aspects to consider related to waste and structure degradation are the biodegradation of organic waste materials, corrosion mechanisms of metallic waste and metallic packaging materials, and degradation mechanisms of concrete structures. Consequences of material degradation might involve gas generation or may enable novel material interactions.

In the future there might be a need to dispose of novel materials arising from decommissioning activities, new reactor technologies, or other sources such as high-activity sealed sources (HASS) or mining/industry waste.

5.3.5.4 Decommissioning

Decommissioning (including plant and infrastructure dismantling, post-operational clean-out (POCO) and site restoration/release) is the final stage in the life cycle of a nuclear facility. Practical experience of decommissioning in Finland has so far been limited to activities associated with the FiR1 research reactor at VTT. However, broad experience exists in Sweden, Germany, UK, USA, etc., and international collaboration may offer exploitable solutions and inform best practice for future decommissioning challenges faced in Finland.

Material characterisation

Detailed site surveys and material characterisation are the first steps in assessing whether items at nuclear sites comprise radioactive waste before decommissioning. Therein, it is vital to understand: (i) the radionuclide inventory present within materials, (ii) the possible depth penetration of radionuclides into materials (e.g. is contamination surface-bound or does it impregnate a material's bulk), and, (iii) the strength of radionuclide binding to materials (e.g. can surfaces be easily decontaminated). When such information is available, decommissioning can be planned and materials can be safely handled, treated, sentenced (or cleared from regulatory control), and packaged for final disposal. In turn, this reduces possible dose impacts for workers, minimises radioactive waste volumes, and permits material recovery. However, surveys and material characterisation during decommissioning can be complex due to access restrictions, material size and compositional heterogeneity, the potential presence of difficult-to-measure radionuclides, and a mismatch in the demand for information on site vs. the speed of analysis (e.g. data may be required rapidly, but materials often need to be transported off-site for time-consuming lab-based analysis).

Reflecting the above, the needs to develop methods that can be used to survey nuclear sites, better characterise heterogeneous radioactive materials, and/or permit radionuclide quantification are recognised.

Decommissioning methods

While many countries are facing significant challenges related to the decommissioning of their nuclear facilities, technologies for LWR decommissioning and dismantling are mature. The main safety concerns in decommissioning are different from facility operation, namely radiation protection (direct radiation and contamination control) and pronounced industrial safety risks. An emerging methodology for decommissioning planning is the use of digital 3D models created with reality capture, for example, and containing a significant amount of data (including measured and/or ever-improving simulated material data, activity inventories, penetration of radiation, shielding). Such use is already well established in the construction industry (building information models, BIM) but currently much less in nuclear energy industry. Additional BIM dimensions beyond 3D cover time, cost, operation, sustainability and safety. Such models are particularly well suited for decommissioning due to the changing plant layout and environment. Visual representation, including virtual and augmented reality techniques, enables efficient communication between project personnel and stakeholders, reducing the risk of erroneous work and enabling the efficient reduction of radiation doses to worksite personnel. Potential uses include work planning and optioneering, radiation safety planning, simulation and training.

There is also the potential for significant efficiency gain with the use of digital tools. An efficiency improvement can be transferred into safety improvements by reallocating the saved resources to activities where they will yield an optimal gain in safety. An example in decommissioning is the final clearance of the site. An advanced automated mapping method, which can prove that all remaining radionuclide concentrations are below the clearance limits, can be of great potential to save resources that can then be allocated to improving the safety of high-risk activities.

At a more general level, optimal regulation of decommissioning would identify the changing risk landscape along with the progress of decommissioning. The focus of regulation can affect the achieved level of safety, given limited resources for the back-end phase of the plant. While radiation risks are declining rapidly, a marked contamination risk remains for much longer, and the industrial risks are at a prominent level over the entire process.

Material decontamination and waste minimisation

During decommissioning and POCO, decontamination of radioactive materials (e.g. surface or near-surface contaminated steel pipework, concrete, etc.) can vastly decrease the volume of problematic LLW–ILW that would otherwise be sentenced for geological disposal. Decontamination methods currently used (or being researched for use) in other countries include wet chemistry, electrochemistry, and physical techniques (e.g. sand blasting or ultra-high pressure water jetting). However, all techniques yield secondary (albeit less voluminous) waste. The composition of secondary waste may differ from previously produced and treated waste, creating new types of LLW or ILW that have not yet been considered. As such, the physical and chemical nature of potential waste must be fully understood.

Accordingly, SAFER2028 welcomes project proposals aimed at the minimisation of voluminous LLW and ILW production during decommissioning. The development of new techniques, or the adaptation of existing methods to national needs, are encouraged. Secondary waste (e.g. dust, aqueous waste, colloids) production/characterisation, and possible management, should also be considered. A better understanding of material contamination may also inform material decontamination methods and thus projects are also encouraged in this area.

Site clearance

After the decommissioning of a nuclear facility has been completed and the area is surveyed to be free from radioactive contamination, the site can be cleared from nuclear safety authority control and taken into other use, left as it is, or dismantled as conventional buildings. However, possible monitoring needs and the definition of what constitutes 'contamination-free' needs to be better defined. Alternative pathways to site clearance, e.g. deciding on possible acceptable levels of contamination with a need for post-clearance monitoring, or options for contaminated material in-situ burial/management could also be considered.

Site clearance (including remaining buildings) is based on sampling and measurements. Systematic ways to analyse the representativeness of the sampling frequency and measurements do not exist yet. Methods to evaluate the representativeness of the sampling frequency and measurements of the site could be developed in SAFER.

5.3.5.5 Alternative waste management concepts

In Finland, a general decision on implementing nuclear fuel single use has been applied due to the current Nuclear Energy regulation and the selected nuclear waste management operation policy. However, the emerging turbulence and possible energy crises related to greenhouse gases and the transition to renewable energy production on a larger scale may also have a big effect on the need for nuclear energy. In addition, the evolution and introduction of small modular reactors (SMR) will create a different demand level for nuclear fuel materials that can change monetary and ideological attitudes towards the recycling of nuclear materials. These foreseeable changes in electric energy consumption and production create the need to be aware of advanced nuclear fuel cycles and their influence on waste management, e.g. in terms of new waste streams.

Separation, transmutation and reprocessing

In the SAFER 2023-2028 programme, the development of the investigations on reprocessing will be followed. In Finland, the final disposal of spent fuel by those responsible for nuclear waste management is based on the fuel being used only once, as per the current legislation on nuclear energy. However, it is important to be aware of the new and emerging nuclear fuel cycles, particularly more closed fuel cycles that rely heavily on recycling the used fuel. There, the partitioning of the actinides is the key factor. In addition, the need for partitioning actinides and lanthanides concerning transmutation (P&T) and decreasing the radiotoxicity and the space needed for the final disposal requires further development of advanced separation methods. This research benefits both the recycling of the nuclear fuel concerning better use of actinides and also the fate of waste as its decreased volume and lower radiotoxicity. Reprocessing research could be implemented through participation in international cooperation projects. The various options and technologies in separation and transmutation techniques are being reviewed from time to time.

Alternative disposal concepts

In Finland, the disposal concepts selected for use are KBS-3V for high-level waste (spent fuel) and disposal to rock caverns (L/ILW). Due to the possible introduction of SMRs in Finland, the disposal of SMR waste needs to be considered. It is possible that SMR waste will not be disposed of using current disposal options, which opens up the discussion to new concepts (see also section 5.1.3.2 Safety and society). Other disposal options for special forms of LILW (e.g. those containing higher quantities of long-life, radio-toxic alpha-emitting radionuclides) may need to be considered. Finally, with the current waste streams, possible changes in the disposal concepts are not excluded, even though such changes are not anticipated to occur.

One alternative disposal concept that has been recognised is deep borehole disposal. Thus-far recognised research topics include, for example, verification methods of suitable bedrock sections for disposal, non-drilling methods for deep bedrock investigations, drill hole investigation techniques in deep holes, and quality assurance in them. Other related topics may also be presented.

Concerning other alternative disposal concepts, research proposals can be presented if there is a basis for their potential usability in Finland.

Advanced reactors

Currently, all the Finnish NPPs as well as most of the NPPs in the world are light water reactors using UO2 packed in zirconium tubes as fuel. However, as early as in the 1950s, various types of reactors were proposed but due to techno-economic reasons, those have not been broadly introduced to commercial use. In the future this may change, as nuclear power may be used for various purposes such as hydrogen production.

Other radioactive waste management

In SAFER, other radioactive waste can be studied, especially if it is processed, placed in interim storage or a final disposal facility located at the nuclear plant site. This kind of waste may include high-activity sealed sources (HASS) and radioactive waste formed during or following their use.

We have high-activity sealed sources from health care, industry and research, which are no longer in use. These sources, which cannot be transported abroad, must be managed in Finland. Currently, although the Ministry of Social Affairs and Health and TVO has an agreement on the interim storage and disposal of state-owned waste at Olkiluoto, some high-activity sealed sources cannot be disposed of in the VLJ cave at Olkiluoto.

Research into the disposal of these high-activity sealed sources is important and can be done in the research programme, assuming the sources will be disposed of in a disposal facility built or planned to be built for the disposal of nuclear waste. Research could deal with the packaging of the sources for disposal and the evaluation of their long-term safety, for example. Challenges of high-activity sealed sources are also discussed in the national programme of spent fuel and radioactive waste,[15] as well as in final report of the national cooperation group on nuclear waste management.[16]

5.3.6 International collaboration

International developments in nuclear waste management are expected to be active during the programme period. For example, the EU nuclear waste directive has already significantly influenced the practices and plans of the industry in the member countries.

In Sweden, a licence application regarding the building and implementation of spent fuel encapsulation and final disposal facilities was submitted to the authorities in March 2011. The Swedish nuclear safety authority SSM (Strålsäkerhetsmyndigheten)

15 MEAE2022; Management of spent nuclear fuel and radioactive waste in Finland: Second national programme under Article 12 of Directive 2011/70/EURATOM of the Council of the European Union, https://julkaisut.valtioneuvosto.fi/handle/10024/163877

16 Final Report on the National Cooperation Group on Nuclear Waste Management; ME-AE, 2019:45. https://julkaisut.valtioneuvosto.fi/handle/10024/161763

gave its own statement in January 2018; on the same day (23.1.2018) Nacka Mark- och miljödomstolen also gave a statement. A decision from the government is pending.

In France, the pre-review of the final disposal of high-level radioactive waste was submitted in 2016 and the authority ASN (Autorité de Sûreté Nucléaire) made a positive statement based on evaluation in 2018. Andra, the French National Agency for Radioactive Waste Management, is currently preparing an application for a licence to build the waste repository.

In the US, the Office of Spent Fuel and Waste Disposition (SFWD) of the Department of Energy (DOE) is executing its research programme on long-term storage, transport and a geological final disposal area. The decommissioning of nuclear plants is also a significant area of focus because of the US's long nuclear programme. It is estimated that the importance of decommissioning will grow worldwide because of the many reactors that are already closed.

Several European nuclear waste management actors have developed low- and intermediate-level waste disposal concepts, because the rate at which waste is accumulating means the pressure to start disposal is increasing. In Sweden, like in Finland, waste disposal is already licensed and the disposal facilities have been in use since the 1990s.

European Commission projects (EC, EURATOM and Horizon EUROPE) have played a very important role in the research and development work of the Finnish nuclear waste community since the end of the 1980s. Together with the former KYT programme, they have formed the core of publicly funded NWM research.

Nuclear waste research funded by the EU is performed in the European Joint Programme (EJP). EURAD (European Joint Programme on Radwaste) is an EJP administrative project that funds radioactive waste management, including research into disposal. The funding of the programme is based on the co-funding principle, i.e. 50% of the funding must come from the EU member countries. The first EJP call opened in September 2018; the research topics were selected based on a wide international enquiry. An organisation participating in the EJP may be placed under one of the following organisational categories: nuclear waste management (WMO), technical support (TSO) or research (RE). Finland has three organisations participating in the EURAD project: Posiva Oy (WMO), VTT (TSO) and the University of Helsinki (RE). Other interested domestic organisations may participate through a cooperation agreement with one of the aforementioned organisations. The MEAE is the programme owner in Finland.

In the field of spent fuel disposal research, most of the research will probably be carried out in EURATOM and SAFER programmes and projects during the first SAFER2028 period 2023–2028. Therefore, good connections between organisations working in EURAD with EC projects like EURAD and PREDIS would benefit the whole Finnish nuclear waste community. EURATOM's research in EURAD is arranged by European Joint Programming (EJP), which is the likely arrangement for the next EURAD 2, which combines the EURAD1 and PREDIS projects under the same programme starting from 2024. In the last call (EURATOM Work Programme 2021–2022) the share of national financing was emphasised. International collaboration is mandatory for research in this topic, and in the new SAFER2028 close collaboration with the EURAD2 programme has to be taken into account.

The Finnish nuclear waste management actors participate actively in the preparation of international recommendations and European safety standards. STUK is working to influence the standards of the International Atomic Energy Agency (IAEA) concerning nuclear waste management, especially through the Waste Safety Standards Committee (WASSC). Specifically, STUK is participating in the preparation of standards and guidelines and by working on IAEA projects (e.g. the International Intercomparison and Harmonisation Project on Demonstrating the Safety of Geological Disposal, GEOSAF). In addition to guideline work, STUK is acting as a Finnish contact organisation in the information exchange systems of the nuclear energy industry maintained by the IAEA (e.g. IAEA Online Information Resource for Radioactive Waste Management, NEWMDB). STUK, WMOs and research organisations also participate in the IAEA MODARIA and MEREIA programmes, which deal with the environmental impact assessments and radiological impact assessments that are part of the licensing process.

NKS (Nordic Nuclear Safety Research) is a Scandinavian cooperation network funded by ministries and power companies. NKS supports the organising of seminars and research on nuclear safety, radiation safety and standby activities. Within the limits of the NKS, four decommissioning seminars have been organised and studies have been carried out regarding the measurement of hardly detectable radionuclides in decommissioning waste, for example.

SITEX_Network is a French non-profit association that aims to enhance and foster cooperation at the international level in order to achieve a high-quality expertise function in the field of safety of radioactive waste management, independent from organisations responsible for the implementation of waste management programmes and waste producers. The aim is to support the nuclear regulatory authorities and civil society. SITEX_Network is open to any institution or individual party with an interest in the independent regulatory assessment of RWM activities.

The Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP) is dedicated to initiating and carrying out European strategic initiatives to facilitate the stepwise implementation of the safe, deep geological disposal of spent fuel, high-level waste and other long-life radioactive waste. It aims to address the remaining scientific, technological and social challenges, and support European waste management programmes.

The international network of research entities EURADSCIENCE (a network of research organisations for radioactive waste management science within Europe) addresses now and over the decades to come scientific excellence in the full life cycle of radioactive waste management from cradle to grave. It plays a strong role in the EURAD programme.

5.4 Mechanical and structural safety of NPPs

5.4.1 Description of the research area

An important aspect of the safe use of nuclear power plants is maintaining the functionality and structural integrity of the systems, structures and components (SSCs). Research programmes providing continuity have helped ensure the safety of Finnish nuclear power plants, which have worked reliably since the 1970s. The planned operating life of new plants under construction and in design is 60 years, while the operating life of the present plants has been, or is being, extended by at least 20 years from their original planned lifetimes, entering what is considered to be the long-term operation (LTO) regime.

In the new SAFER2028 programme, there is a need to maintain and even increase expertise in this area, producing the additional information necessary for improving the life cycle management of the plants and their materials, and the accompanying analysis tools. The reliability of the materials under all conditions related to the use of the plants shall be considered. This includes knowledge of the manufacturing and repair technologies as well as the inspectability of the components to identify when aged material renewals must be carried out. This includes consideration of new technologies such as component manufacturing by additive manufacturing, novel tools for non-destructive examination, and online condition monitoring methods. Likewise, the impacts of new performance demands presented by load-following operational modes to accommodate the impact of renewables on the grid, and of SSCs in new configurations such as those of SMRs, are important new considerations.

5.4.2 Objectives of research

A common goal for research in this area is to ensure reliability by ageing management throughout the plant's life cycle. Because the area is very broad, the research plan presents the key areas of focus for the new programme period. The research area connects structural safety and materials into a research entity that benefits from expert collaboration, and that can form a broader view of plant life cycle management. A particular goal is to secure the necessary knowledge and expertise to support the existing Gen II plants in operation and conduct method validation.

The aim of the research is to increase knowledge that supports the long-term and reliable use of nuclear power plants, particularly with respect to matters involving the integrity of barriers or material issues that affect the reliability of the safety functions. The research will target the ageing phenomena of the existing equipment and structures and the correctly timed management of their progress.

The research topics are grouped into the following main areas: Ageing management (primary and secondary system components, civil structures, other system structures and components), new methods and materials (non-destructive testing, monitoring, small modular reactors, additive manufacturing) and safety-relevant loads (fragilities, seismic hazards, fire safety engineering, validation of methods and tools).

5.4.3 Ageing management

The ageing of systems, structures and components, as well as changes in the characteristics of the materials due to ageing, shall be considered during the design, construction, operation, condition monitoring and maintenance of a nuclear power plant. The systems, structures and components important to safety have to meet the design basis requirements with the necessary safety margin throughout the service life of the plant. Understanding ageing of the materials is, however, a key requirement for ageing management. Ageing management is important in many areas of the plant, not only in the primary and secondary system components, but also in civil structures, as well as in the materials of other system components, such as cables, coatings and fibreglass pipes.

To optimise the ageing management, the ageing process, preventive actions and mitigation strategies assessment requires novel and comprehensive development of assessment methods, analysis tools and approaches. Ageing management requires the recognition of failure mechanisms and the assessment of the propagation of existing failures, which involves determining the size and assessing the rate of crack growth and propagation. Therefore, it is essential to understand the ageing mechanisms and the damage susceptibility of different materials, and have appropriate computational tools for assessing their impact on structural integrity. In the ageing management, the cumulative effect of ageing should also be studied. The failure of a component may be due to two or more ageing mechanisms affecting the component simultaneously, e.g. corrosion and fatigue. To be sure of the safe operation of the components, the synergistic interactions must be determined.

The durability of different components is affected by the manufacturing technique, the environmental conditions, and the structural loads. Considering lifetimes of at least 60 years are now expected for Gen II and III plants in Finland, the possible ageing phenomena must be considered when modernising the operating nuclear power plants, as well as when building new ones. New ageing phenomena may also have to be taken into account when the long-term durability of a material is assessed. With long construction times, this includes consideration of potential degradation of installed components while awaiting plant completion, and appropriate preservation and mitigation strategies for them. Similar non-operational exposure considerations are also relevant for steam generators during outages, for example, where crack growth has been shown to be markedly higher. Likewise, plant transients are important in the long-term durability of the component. During operation, ageing management information can be gathered through condition monitoring and non-destructive examination methods.

The aim of ageing management research is to produce research results through experimental work and computational work. These include phenomenon-based experimental research and modelling, benchmark studies, the development and implementation of new research methods, and research on representative experimental samples and real samples. The representative data used shall be as close as possible to the actual environment to identify the correct ageing mechanism. The VTT Centre for Nuclear Safety and its hot cell facilities provide good ageing management research capabilities for irradiated materials.

Ageing management involves two consecutive steps:

- a comprehensive integrity assessment of the ageing mechanism
- preventive actions and mitigation

A comprehensive integrity and ageing assessment requires the application of realistic starting points such as loading conditions, material properties, environment and geometry. These starting points can either be determined by direct analysis or from measured data. Uncertainties in either the ageing mechanism analysis procedure or the starting points may give rise to the need to apply a probabilistic approach. To simulate the ageing process in a realistic way, active ageing mechanisms shall be coupled. Some ageing mechanisms can be assessed experimentally and others numerically.

In the second step of ageing management, the time-dependent ageing simulation results can be used to design preventive actions and a mitigation strategy. Preventive actions may prevent the ageing mechanism from occurring or reduce the effect thereof. Examples are load reduction and environmental improvements. Mitigation strategies can be supported by inspection activities.

The two-step ageing management approach can significantly support risk-informed in-service inspection (RI-ISI) and LTO programmes.

5.4.3.1 Primary and secondary system components

This research area includes the ageing management of primary and secondary system components of the nuclear power plants, which involves the reactor pressure vessel, its internals components, steam generators, pressuriser and associated piping, pumps and valves. Research is still required on the ageing of reactor vessel steels with lifetime extension, reactor pressure vessel internals of stainless steel, high nickel and nickel-based alloys, welds and dissimilar metal welds in components, environmentally assisted degradation, and water chemistry effects more generally.

Some of the recognised ageing mechanisms in primary and secondary system components are:

- irradiation embrittlement of the reactor pressure vessels
- impact of neutron radiation on reactor pressure vessels' internal materials (IASCC, swelling)
- fatigue, including environmentally assisted fatigue
- stress corrosion cracking (stainless steels and nickel-based materials)
- thermal ageing
- erosion corrosion or flow-assisted corrosion (FAC), including cavitation and droplet corrosion
- oxidation or other corrosion phenomena.

While it is essential to identify the correct ageing mechanisms, attention also needs to be paid to the transferability of laboratory results to cracks in structural components. In particular, the numerical fracture mechanics research needs to support the experimental research related to the irradiation embrittlement of RPV and piping materials. Furthermore, improved fracture mechanics techniques to assess the integrity of embrittled components shall be developed. The criticality and growth behaviour of non-idealised real cracks and cracks under complex stress fields needs to be clarified, as well as cracks located at material interfaces. The effect of crack tip constraint in structural integrity analysis of the RPV needs subsequent research. The applicability of local approach, damage and micromechanical models in describing material degradation can be reviewed and developed. Research can focus on methodologies related to the interaction and the combination rules of several small indications or cracks.

Further development of probabilistic and risk-based approaches is needed, in particular to include phenomena arising from the long-term operation of the NPPs. An important aspect of the research approach is to facilitate planning for risk-informed in-service inspection programmes. To ensure the reliability of such an approach, it is important to qualify the applied probabilistic structural integrity analysis tools and compare the results with those of third-party and commercial tools. The incorporation of decades of operational experience is valuable in calibrating the probabilistic models predicting plant ageing.

Reactor pressure vessel and internals

Radiation embrittlement is recognised as a critical ageing mechanism in the Loviisa plant's reactor pressure vessel (RPV). The commissioning of new plants requires reliable estimates of the rate of RPV embrittlement up to 60 years. Radiation increases ferritic steel strength and decreases its toughness, making brittle fracture of the weld materials in particular possible at higher temperatures. Knowledge of radiation embrittlement ensures the lifetime management and safe use of RPVs, making RPV embrittlement an important topic in this programme.

The fracture mechanical behaviour of irradiated materials and the actual mechanism of radiation embrittlement are not fully understood. The research and modelling of fracture toughness with more detailed computational analyses shall still be done to ensure the durability and structural integrity of ageing plants during the LTO. In addition, the experimental and modelling capability shall be suitable for analysing the structural integrity of the new plants. The aim is to increase the knowledge of fracture toughness and microstructural characteristics of the reactor pressure vessel steel. This research shall include, in addition to conventional materials, the new type of Russian steel.

In this plan, the focus of research should be on the mechanism of embrittlement together with the effects of inhomogeneity, which means that the microstructure shall also be studied. Improved technology or tools for the prediction of ageing behaviour are expected to be found. Current knowledge of material parameters is incomplete, which makes the verification of calculation methods difficult. There is little information on the effects of radiation on the properties of RPV coating. An approach based on the material's fracture resistance has been developed. The effects of the environment and the loading rate on fracture resistance have been investigated.

Standard fracture mechanical considerations based on the master curve still require further development as well. For example, the miniature C(T) specimen technique still requires more development work to make the technique more applicable. The obtained results shall be of high quality, however. As numerical analysis methods improve and are taken into use, there will be a need for more accurate material characterisation, particularly in relation to coatings and welds. The research on materials that have been in operation might provide important information on the critical weld. LTO and possible extension of the plant lifetime may also require testing of the base materials.

In order to ensure reliable fast fracture prevention analyses of ageing RPVs, the improvement of probabilistic brittle fracture analysis tools is needed to accommodate the reduced margins due to material embrittlement.

Within the RPV itself, the stainless steel and nickel-based reactor internals components accumulate even greater radiation exposures, which can lead to degradation of their structural integrity. Neutron irradiation leads to hardening and simultaneously loss of uniform ductility. In the event of crack initiation, propagation can be rapid due to the radiation-induced loss of stain hardening capacity. Furthermore, the primary water environment can promote crack initiation and propagation, depending on the particular water chemistry in the region of cracking. Irradiation-assisted stress corrosion cracking (IASCC) susceptibility has been studied extensively around the world, but it has proven difficult to predict, indicating it is still inadequately understood. Currently many plants in Europe and the US are experiencing bolt failures, even in newly-installed bolts. The apparent unpredictability indicates further understanding must still be pursued to ensure confidence in the structural integrity of components in domestic plants.

Particularly at high levels of dose accumulation, cavities can form within internals of materials. As the amount of cavities accumulates, swelling may result. The formation of cavities has been found to be dependent on radiation temperature, and therefore so far LWR internals have not suffered significant swelling. However, because swelling is a non-linear process, it is important to understand the margins remaining in power plant reactors as they enter LTO regimes.

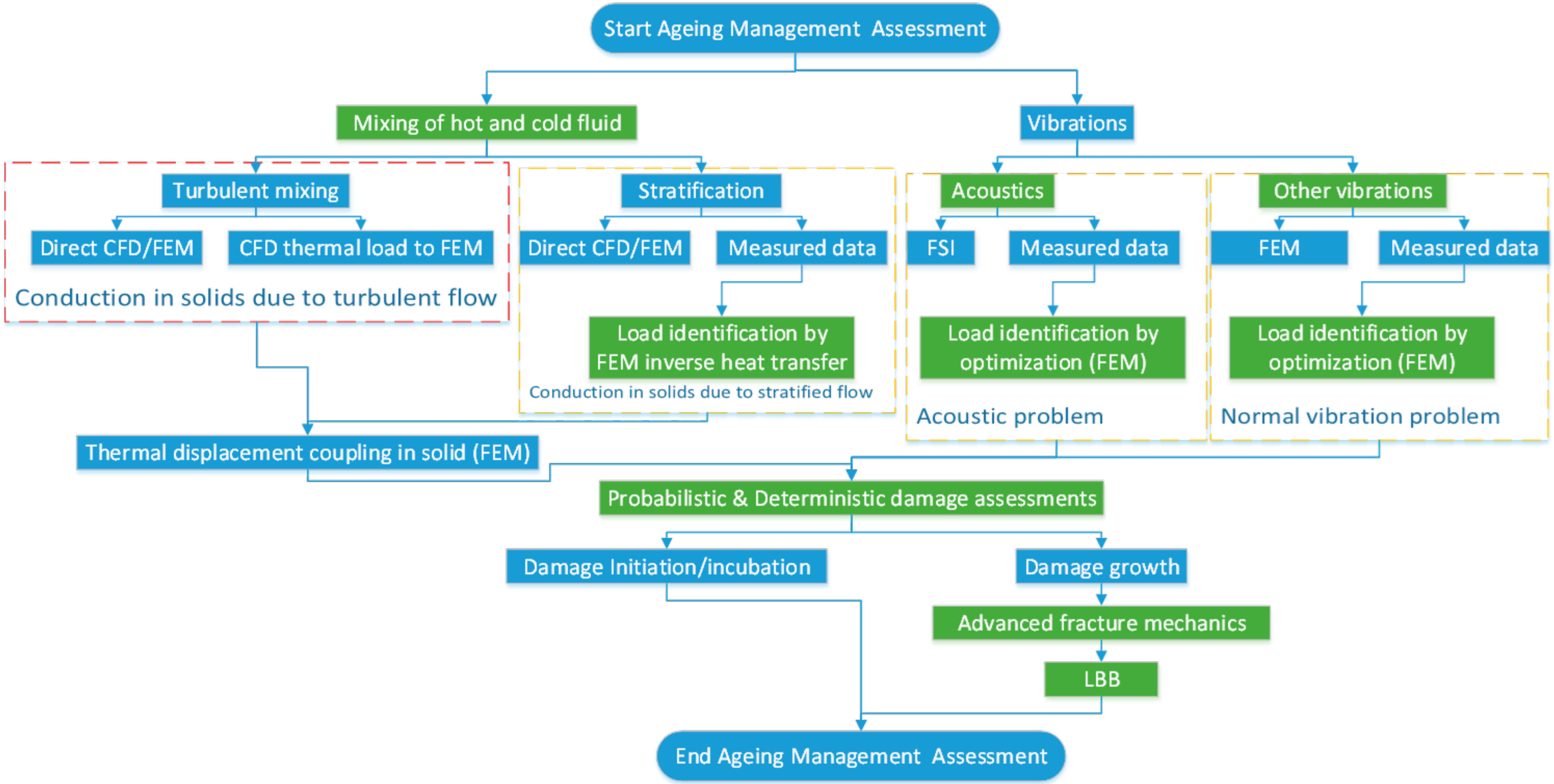
Material fracture toughness changes can also occur as a consequence of the thermal ageing of structural materials. One possible mechanism leading to such changes in fracture toughness in ferritic materials are phosphorus segregation to grain boundaries. This is called temper embrittlement and it can occur particularly in the heat-affected areas of welds. Various precipitations in nickel-based structural materials may also lead to changes of fracture toughness of those materials. Thermal ageing is highlighted as operating temperatures increase, and due to this, these phenomena may become significant in new plants. This ageing mechanism has to be considered in some components at the operating plants and also at lower operating temperatures when moving into LTO.

Producing experimental data on the use of irradiated materials would benefit from international cooperation. Testing of irradiated materials at VTT's Centre for Nuclear Safety has started, which greatly facilitates such collaboration. Research on Barsebäck reactor pressure vessel material in cooperation with Energiforsk has also been very important in taking those facilities into use. Other primary and secondary circuit materials received from the decommissioned plants, e.g. by collaboration with the SMILE programme, or even from the existing domestic plants, should also be used in ageing management research. Research collaboration can yield valuable information on ageing phenomena as well. International collaboration is valuable both concerning knowledge management and when the larger research projects are needed.

Piping and connecting components

In terms of material quantity, a large proportion of the primary and secondary circuits involves various kinds of piping and associated components. Piping in particular is subjected to various degradation and ageing mechanisms. In this area, fluid-structure interaction and associated computational model development are important research topics. This approach is illustrated by an example from TVO, shown in Figure 5.1, which shows that such assessments need to accurately capture fluid flow and its effects on the surrounding structure, as well as the interaction between the fluid and solid material. The development of novel techniques that are able to perform flow analysis faster and at reduced computational cost are needed. Further research is required to develop more realistic methods to predict thermal stresses and material degradation caused by temperature fluctuation and fluid mixing, e.g. by utilising experimentally measured data. Techniques related to the modelling of thermo-hydraulic shock loading and acoustic phenomena and their consequences on piping components are not fully established.

Figure. 5.1. Ageing management assessment of piping, as approached by TVO.



Better understanding of vibration phenomena and their effects on short- and long-term structural durability is necessary. This induces the need for research related to the causes and effects of piping vibrations, flow-induced vibration and their mitigation. Novel structural dynamics techniques focused on the sources of vibration in the primary circuit components and the propagation of the component induced vibration or pressure waves to the whole circuit can be developed. New approaches are needed for the monitoring and prediction of the component state, condition and integrity. These shall be based on vibration measurements and supporting computational and mathematical models.

Further development of probabilistic and risk-based approaches is needed, in particular to include phenomena arising from the long-term operation of NPPs. An important aspect in the risk-based research and developments is to provide support for the planning of risk-informed in-service inspection programmes. To ensure reliability it is important to qualify the applied probabilistic structural integrity analysis tools and compare the results with those of third-party and commercial tools. The incorporation of decades of operational experience is valuable in calibrating the probabilistic models predicting plant ageing. In order to ensure reliable fast fracture prevention analyses of ageing RPVs, the improvement of probabilistic brittle fracture analysis tools is needed to accommodate reduced margins due to material embrittlement.

Furthermore, it is valuable to improve the connection between probabilistic structural integrity assessments and the PRA. Re-engineering and tailoring of the physics-based degradation models are needed to be more in line with the approaches inherent in the PRA analyses. Methods to combine the damage probabilities of similar cross-sections in the same pipe seeing the same loads shall be developed so as not to overestimate the damage probability on the whole system or plant. With relevance to the long-term reliability of plants' SSCs, probabilistic and other methods that are able to consider variations in the input parameters allow the quantification of the overall safety margins in structural assessments. The development of efficient probabilistic algorithms based on physical and mathematical relations between input parameters to output responses is needed, for example by expanding the domain of uncertain input parameters for best estimate calculations with new algorithms that were not considered previously due to limitations in existing probabilistic algorithms.

An important research topic is the coupling of actual plant measurement data such as mechanical vibrations, pressures and temperatures with associated structural models. The measurement data can be utilised by updating and calibrating numerical models with optimisation routines based on actual plant data, for example using machine learning techniques. Based on correct physics and calibrated with actual data, the numerical models can be used to make predictions of the plant state and quantify and identify the loads acting on the piping system and its components probabilistically. Another potential research topic is the development and application of the digital twin concept for nuclear applications.

Further development and application of the leak-before-break (LBB) concept is valuable for increasing our understanding of how to apply the approach for ageing piping and new builds, and discovering the best practices to demonstrate LBB. The application of the LBB argumentation in cases with complex loads and nonlinear material response, such as residual stresses and crack closure, requires additional research. After the subcritical crack growth phase, accurate descriptions of crack breakthrough and growth patterns during the leak phase are essential to determine the crack geometry to be compared to the limit load. Reliable leak rate analysis requires accurate modelling of the crack opening area. It is important to further develop the interface between LBB analyses and thermal hydraulics modelling. To enable a wider application of LBB evaluation of the safety factors and required margins in the current LBB, assessment is necessary. Finally, coupling the LBB assessments with probabilistic analyses needs further development and qualification.

Research can be focused on special-purpose computational techniques and integrity assessment methods. The simulation of welding and the realistic prediction of welding deformations and residual stresses remains important, including the relaxation of the residual stresses during plant operation. There is a need to further develop and take into use efficient, accurate and qualified welding modelling tools. The development and application of fitness-for-service methods for nuclear applications has evolved recently and can be further improved within the programme. The interface between the component-level integrity assessments and plant-level response simulations needs development. An example is the coupling between component vibration qualification analysis and plant response spectrum analysis.

It is worthwhile comparing and harmonising requirements from various design standards and evaluating the continued use of components. Furthermore, research related to streamlining the qualification process for low safety class components is needed. The development of computational methods needed to support and evaluate different repair techniques shall be continued.

More specifically, the research plan presents the key areas of focus for the new programme period. Science-based methods for fatigue shall be emphasised, including the topics of environmentally assisted fatigue, thermal fatigue (e.g. Alloy 690 used e.g. for pressure vessel heat transfer pipes at Olkiluoto 3, high-temperature regions in the primary circuit) and vibrations. Additional knowledge is needed on the combined effect of environmental and load factors as well as material types, e.g. loadings of the structures and components, and the geometry of systems can also cause severe vibration of the components. The cause of vibrations is not always known, so it will be an important research topic.

Fatigue performance of components exposed to water may be adversely affected. This has been demonstrated by decades of laboratory research. Such experiments are difficult to perform in a manner that remains compliant with the fatigue design basis, and leaves open questions yet to be fully answered. Nevertheless, environmental effects need to be addressed as part of analyses to determine margins to cracking in fatigue sensitive locations. The assessment of fatigue in practice is multidisciplinary teamwork involving expertise in stress analysis, materials, fluid-structure interaction, water chemistry and non-destructive evaluation. Excessively pessimistic penalty factors for materials in reactor coolant unnecessarily hinder this teamwork and are a particular challenge for long-term operation, including prioritisation of RI-ISI focus areas. Mechanistic understanding of the phenomena behind environmentally assisted fatigue, via responsible experimental research, is the basis for reducing excess conservatism in penalty factors and assisting in demonstrating sufficient safety margins to fatigue cracking.

Water chemistry effects

The environment of ageing also plays an important role in ageing mechanisms. Primary circuit water has plant-specific water chemistry, and therefore BWR-, PWR- and VVER-type reactors each have different kinds of ageing mechanisms depending on the particular structures, choice of material of the component, water chemistry and stressors. In the primary and secondary circuit, the main factors influencing corrosion in addition to the material include pH, temperature, flow velocity and impurities in the water. There are several factors that have to be known in the ageing management assessment, and which are still partly unknown.

Water chemistry affects all corrosion-related ageing phenomena in nuclear power plants, as well as activity build-up on primary loop surfaces. Water chemistry issues are linked to materials' performance as a whole because the water chemistry of the system impacts directly on the corrosion of materials. Corrosion in turn plays an important part in the initiation and growth of cracks and the formation of corrosion products depositing on fuel cladding (crud) or steam generator surfaces, for example.

In terms of ageing management, the main tasks of water chemistry are to monitor and manage chemical conditions in the process. The chemical programmes cover the primary and secondary circuits of old and new nuclear power plants, intermediate circuits, component cooling circuits, generator water-cooled circuits, and other auxiliary systems related to the previous ones. Chemistry programmes affect all those devices and components that are in contact with the process medium.

Specific areas of high importance related to the water chemistry of Finnish nuclear power plants have been identified and are listed below.

- One of the topics in the area is flow-assisted corrosion (FAC) in high flow rate sections. This phenomenon is of importance with regard to new reactor designs (e.g. only heat-generating) or upgrades to existing ones. In addition to causing wall-thinning in tubing, FAC plays a major role in producing oxide particles depositing on fuel cladding in the core area or on PWR steam generator surfaces. FAC can be affected both by water chemistry and material selection, and it is known to be sensitive to temperature.
- Hydrazine (N2H4) is commonly used in PWRs as an oxygen scavenging agent, both in the primary circuit during start-up and in the secondary circuit during operation and shut-down periods. However, hydrazine use is becoming more restricted and may even be banned due to its toxicity. Alternative water chemistry regimes replacing hydrazine in PWRs are actively sought and form a possible research topic.
- Impurities and their enrichment in areas of restricted flow form a threat to the integrity of pressure boundaries of both BWRs and PWRs. On the secondary side of PWRs, stress corrosion cracking (SCC) is caused by the enrichment of impurities due to boiling. In BWRs, for example, chloride and sulphate transients are suspected of enhancing stress corrosion cracking in dissimilar welds and pressure vessel steel under the cladding, for example. Research work aimed at understanding the mechanisms of impurity enrichment and developing models for the phenomena is internationally recognised as a relevant area.
- Small modular reactors (SMR) are currently being developed worldwide, and a contract to build the first set of SMRs in Europe has just been announced. In Finland, several cities have announced their plans to study the possibility of acquiring SMRs for local heat and/or electricity production. The water chemistry of some SMR reactors will likely differ markedly from current operating reactors. This is an area where at least a close follow-up of the development is necessary, together with the identification of the main water chemistry-related issues.

Other possible research areas are listed below.

- Regarding new plants, the passivation procedure of primary circuit surfaces during the Hot Functional Testing (HFT) period is of high importance in reducing activity build-up during the following operational periods.

Therefore, the optimisation of the procedures and the water chemistry regime used during HFT of both LWR new builds and small modular reactors (SMRs) is an important research area.

- Most of the activity within the primary circuit of both BWRs and PWRs resides within the crud (deposit forming on the fuel cladding). The release of activity from crud into the primary coolant (and further deposition on other primary circuit surfaces) is aggravated by operational transients (including start-up and shutdown periods). Water chemistry regimes minimising crud formation during operational periods and the reduction of activity release and impurity enrichment during transients form other research areas relevant to reducing activity build-up. Likewise, deposit formation on the PWR secondary side aggravates local water chemistry conditions, possibly leading to stress corrosion cracking (SCC), which continues to be the main cause of failure in steam generator tubing. In this area, a better understanding of the parameters affecting oxide particle formation (the source term), deposition/re-entrainment and magnetite hardening processes would help to develop modelling tools to predict and mitigate the phenomena.
- PWRs use LiOH to elevate pH in the primary circuit, while VVERs use KOH. Due to the high demand for Li for batteries, its availability in the future is followed by a question mark. Large international programmes are currently carried out to lay the basis for possible decisions to start using KOH in PWRs. This is a research item that is expected to need to be at least followed carefully.

It should be noted that research in other areas of water chemistry can be included in the research programme, and the examples given above are not meant to be an exhaustive or exclusive list of research topics.

5.4.3.2 Civil structures

Concrete is a strong and durable building material. NPP concrete structures are structurally designed with high safety factors.

The ageing management target is to advance the assessment of the safety performance of civil engineering structures. There are still scientific and technological problems that currently hinder the safe and long-term operation of nuclear power plants' safety-critical concrete infrastructure. Proper understanding of deterioration physical phenomena and ageing mechanisms requires research based on experimental and theoretical studies and modelling techniques. There are no guidelines on how to interpret the results of both destructive and non-destructive tests. Concrete material properties are normally studied by destructive testing, sometimes with thin slices (petrographic examination). Non-destructive testing (NDT) will be used more in the future.

More research is needed to determine new design values (guidelines) for aged/damaged structures (to support the LTO of NPPs). Conservative approaches are used during design and defined by codes and standards employed throughout the life of the plant. For example, a concrete chemical reaction like alkali silica reactions (ASR) have an essential influence on concrete tensile strength but not much compressive strength. Better physical understanding of all relevant ageing mechanisms and their driving parameters are needed in the future. One possibility is to use probabilistic assessment instead of deterministic calculations for aged structures to get a better understanding of the safety margins of the structural behaviours.

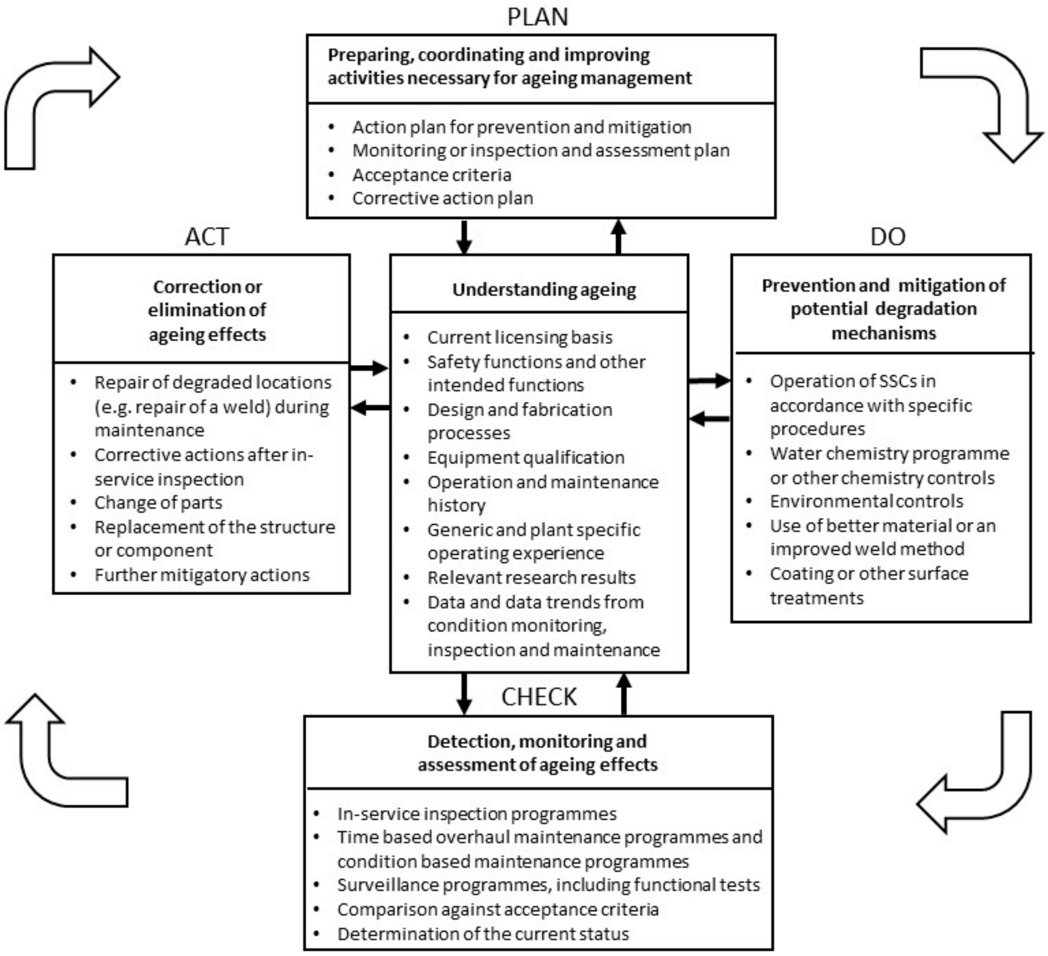
Major safety-related concrete structures are safety class 2 concrete structures (reactor containment and bearing structures of the safety class 1 components bearing like a concrete biological shield structure) and safety class 3 concrete structures (reactor building, spent fuel pools, safety-related cooling water structures, etc.). Typically those structures are very massive reinforced concrete structures with large structure thickness (typically >1.0 m), dense and complex reinforcement detailing, and have a key role in mitigating the impact of extreme environmental loading events such as earthquakes, floods, aircraft impacts, and internal loads like fire, loss of coolant accident (LOCA), severe accidents, etc. on NPP safety. Concrete structures can also include pre-stressed steel, steel liner plates and structural steel. Those structures differ from normal reinforced concrete structures. Typically an ageing management programme (AMP) ensures that those structures meet their functional and performance requirements and maintain adequate structural margins during operation time.

More guidelines are needed for surveillance (performance estimation), inspection, monitoring, condition assessment, maintenance and repair of structures.

Concrete ageing is a complex mixture of factors concerned with materials, environments and their time-dependent interactions. When concrete ages, changes in its properties will occur as a result of continuous microstructural changes. Also physical or chemical attack can lead to internal expansion, cracking, leaching, etc. The effect of age-related degradation often leads to a reduction in mechanical and durability properties. Long-term operation (LTO) has become more important.

The IAEA Safety Guide SSG-48 provides a generic approach for the effective ageing management of NPP SSCs. Those guides formulates activities: Understanding, prevention, detection, monitoring and mitigation of ageing effects on the concrete structures in NPPs.

Figure 5.2. **Systematic approach for ageing management of concrete SSCs, IAEA Safety Guide SSG-48**



Systematic approach for ageing management of concrete SSCs

In the future it will be important to more carefully study mix design, cement characteristics, aggregates characteristics, etc., environmental exposure and applied loads, as well as identifying those for which ageing degradation has the potential to cause concrete structure failure and use monitoring and trending of ageing effects.

Typically, acceptance criteria may be found in design codes and standards. The determination of common acceptance criteria is still difficult because of differing materials, functional requirements, behaviour characteristics, exposure conditions and other conditions. The need for sufficient margins should be taken into account in these acceptance criteria. Material physical properties can also change due to chemical reactions (ASR, thaumasite corrosion, etc.) and can have an influence on load bearing capacity in certain loadings (earthquake, dynamic, etc.). Further advancements in understanding of the ageing phenomena is needed. This includes understanding of degradation mechanisms (accuracy, sensitivity, reliability and adequacy of the examination methods) and their consequences. There is a need to be able to make reliable long-term predictions of ageing and its effects. Model parameters must be validated against data from laboratory experiments and most importantly from operating experience feedback.

Containment liner corrosion problems have been found in many countries. Embedded liner inside concrete, surface liner and also pool liner ageing phenomena shall be researched. Other steel structure issues, such as containment penetration structures' ageing phenomena, are not well known. Change works use a lot of post-installed anchors and degradation mechanisms are not known in different circumstances. The same is true with aged rock anchors.

In concrete structures there are also steel structures that may corrode in different ways depending on the material and the location of the materials in question. In interim spent fuel storage, spent fuel pools have experienced leakages. The mechanism of the pool liner cracking leading to leaks is unknown. The amount of leakage determines partly how the concrete will be affected after exposed to fuel pool water. This corrosion phenomenon needs further research.

The long-term durability of concrete structures for nuclear waste disposal applications is one potential research area.

Climate change induced by an increase in concentrations of greenhouse gases will affect changes in seawater levels and more extreme weather events like windstorms and extreme rainfall events. The influence on civil structures is not fully known. In the future, low carbon dioxide concrete will be developed.

5.4.3.3 Other system structures and components

Polymer-based materials are used in many applications in nuclear power plants, e.g. cables, sealants, coatings, pipings, and as part of electronics in instrumentations. Since the application of polymers in nuclear facilities are broad, they are also exposed to a broad range of environments with regard to temperature, radiation, moisture and atmosphere. Currently there are two main topics in polymers that are important: 1) Ageing mechanisms and tools for predicting the remaining lifetime of different components, and 2) Development of non-destructive methods for cables.

Understanding how polymer composition and the environmental parameters affect the ageing of these components is vital when estimating their remaining lifetime, as well as their performance in DBA scenarios. The lifetime estimations currently rely on experimental data obtained by accelerated ageing. The accelerated ageing is usually performed at elevated temperatures or with a large dose rate compared to the actual ageing conditions. It is known that the activation energy for ageing can vary as a function of ageing temperature, and similarly, high dose rate irradiation may expose the samples to diffusion limited oxidation (DLO) yielding in unrepresentative ageing treatments. Thus, solid research topics regarding polymer ageing could include studying the effects of polymer composition on ageing, the role of activation energy and DLO in accelerated ageing, or the development of tools predicting ageing at different temporal and spatial scales.

A nuclear power plant can contain between 1000–2000 km of different types of cables used as part of various instrumentation and control systems, such as motors and actuators for power-operated valves that may have safety relevance during a design-based event. Managing the condition of these cables will be the subject of growing interest as nuclear power plants age. Currently, the most recognised condition monitoring parameter for cables is elongation at break, which is defined by a destructive tensile test. In order to perform representative tests with this method, surveillance samples are required, which in many cases are not available. Thus, there is a clear demand for a non-destructive monitoring method for cables. Developing such techniques requires proof-of-concept on the sensitivity towards detecting ageing, setting proper end-of-life criteria, and the development of on-site measurement procedures. The effects of ageing on fire properties has not yet been resolved.

In some systems, fibreglass-reinforced piping is used. At the age of 40+ years the material still functions well, but the aged material properties are not well understood. If the plant wants to perform system changes, it will be necessary to gain a better understanding of the material properties. Therefore, these have to be studied, preferably first via a literature study and if necessary later via dedicated tests.

5.4.4 New methods and materials

5.4.4.1 Non-destructive testing

Non-destructive testing (NDT) methods are important tools in every phase of the material research and use. New techniques could improve the reliability of the inspection and reduce the inspection time. The ageing management of an NPP would benefit from improvements to NDT techniques. Novel techniques that give the possibility to understand the current condition of the inspection target and allowing more reliable lifetime analysis are valuable to further evaluation and decision-making.

Non-destructive testing or examination during in-service inspections of NPPs is conducted in challenging spaces and areas with access restrictions and/or difficult geometries. An example of this is objects restricting and blocking the scanning of a weld leading to one-sided inspection. In those cases, the effect of geometrical challenges to defect detection must be taken into account. A good example of access restrictions is the inspection of a nozzle's inner radius with no access to the inner diameter due to the blocking element. Advanced research on NDT methods is needed to overcome the attenuation due to the large distance from the accessible inspection surface. Also, the accuracy of the given inspection results is expected to be more accurate and reliable. It is important to be able to rely on the NDT results of crack opening to the surface, even with high attenuation and hard geometry targets.

One specific topic that is entering the nuclear industry and further to the field of NDT is the inspection of additive manufactured (AM) components. The complexity of the AM components' geometry and material structure and anisotropy provides a challenge to NDT, especially for volumetric inspections. Novel methods need to be developed to allow the cost-effective and accurate inspection of new materials like AM components and to properly see the limits and requirements for the inspection and qualification.

It is expected that machine learning will be used as part of the NDT inspection within the timeframe of the SAFER2028 programme. Data evaluation with machine learning has already been successful in the laboratory environment. Also, AI-assisted analysis is entering the field of NDT, such as for the evaluation of material properties combining several NDT methods using neural networks. In particular, the ageing of NPP components might be assessed by NDT, if good accuracy is achieved in observing the material changes. The assessment results would be applied to evaluations of the risks of stress corrosion, embrittlement, or fatigue of the components of long-term operating plants. In monitoring new power plants, it would be possible to carry out pre-service inspections for comparison of further ageing.

The research on non-destructive test methods of polymer materials should continue. It could provide new information on the ageing of electrical and I/C components in nuclear power plants, for example.

NPP concrete structures are exposed to physical, chemical and mechanical factors that can cause deterioration. Poor construction and deterioration can result in the loss of strength and the unsafe conditions of the structures. To ensure the safety and integrity of NPP, non-destructive testing is carried out during the in-service lifetime. The research on finding efficient methods for porous concrete structure is important to continue in the SAFER2028 programme. In particular, the corrosion detection of the NPP containment steel liner is of interest.

5.4.4.2 Monitoring and online monitoring

Inspection and monitoring data provides information on actual structural and environmental conditions, and is a baseline against which ongoing performance can be evaluated. This is valuable for tracking degradation progress, and for determining whether design assumptions for environmental conditions are being achieved in practice. Data needs to be reviewed to confirm that any changes in structure condition are stable and predictable, and to monitor the effectiveness of mitigation measures. Data trends from in-service inspection/monitoring/maintenance history is important. First, the data has to be collected (inspection, test, monitoring) and then evaluated against the design basis and acceptance criteria; after that, trending data is analysed and extrapolated. This is followed by the development of criteria for the assessment of ISI and monitoring findings to allow proper judgement about the condition of concrete structures, and the development of inspection and monitoring techniques and methodologies, especially for the assessment of the ageing process in inaccessible locations (e.g. behind liners, reinforcement in massive structures), and that consider the whole structure.

Development and demonstration of intelligent plant condition monitoring systems are needed in the future.
Sophisticated data analysis tools and the development of a decision-making framework is a future need.

An NDT investigation for essential concrete structures is needed at certain intervals to find out whether any changes have occurred.

The monitoring and measurements programme challenges include:

- Deformation measurements (local, global, 3D)
- Temperature measurements (inside concrete and surface)
- Surveillance of concrete crack growth
- Surveillance of possible leakages (containment liner, pools)
- Containment leak rate test
- Surveillance of properties of concrete, reinforcing steel, prestressing steel and expansion joint materials
- Containment tendon forces (load cells)
- Grouted tendon system condition approval method
- Monitoring and measurements in seawater structures

- Surveillance of coatings
- Containment pressure measurements
- NDT monitoring
- Embedded wireless sensors
- Corrosion monitoring
- Concrete chemical reactions monitoring
- Online monitoring (e.g. pool leakages)

On the process system side, monitoring has evolved since the Loviisa and Olkiluoto plants were built and became operational. Examples for this are the dedicated valve, acoustic and humidity monitoring systems in the OL3 plant unit. Data from these systems is post-processed and provides valuable information as to the functionality of the valves, loose parts inside piping or very small leakages in strategic areas. Existing and new systems as well as associated post-processing software are developed all the time and apparently at an increasing pace. In Loviisa, a video-based vibration measurement system is in use where the software can determine and animate Eigenfrequencies and associated Eigenmodes. It is important to study systems like these as well as other available systems and systems that are still under development. Firstly, it would be important to perform a literature study and establish their potential use, as well as verify their reliability. For this it is significant to be in contact with the NPPs and to find out in which areas monitoring is necessary. Secondly, the most significant systems shall be tested. During the testing, possible pitfalls in the testing and post-processing methodologies shall be studied and listed, as once in the plant these must be avoided.

5.4.4.3 Small modular reactors

The mechanical and structural safety of SMRs is a topical and quite novel field of research. Identifying the most safety-relevant issues related to SMRs requires a wide development of know-how. The variety of SMR designs and technologies presents a challenge for all Finnish stakeholders, as designs typically include something new to the nuclear sector, such as new reactor types, materials, manufacturing methods, etc. That is why new types of reactors and related material issues should be addressed from mechanical and structural viewpoints. In addition, the structural integrity of new building materials and methods should be studied.

It is usually claimed that SMRs are safer than the current large NPP technology. It should also be possible to prove and verify this higher level of safety. SMRs may include passive systems or components and SMRs may utilise different operational conditions to existing plants. Instead of electricity production, SMRs may be used to produce district heating or industrial process heat (e.g. production of hydrogen).

Components of SMRs may include completely new geometries, materials and manufacturing methods. Thus, research on reliability, structural integrity, ageing, manufacturability and inspectability related to these new solutions should be researched in order to gain sufficient expertise on safety-related issues. An example of a new manufacturing method that may be used is additive manufacturing. Research on what types of challenges SMRs could pose in terms of fire safety, fire and flood hazards would be justified.

Containment solutions and pool structures of SMRs may be different to conventional NPPs. For example, a steel reactor pressure vessel may be inside a slightly larger steel containment vessel. These vessels may then be submerged in a reactor pool. Also, reactors intended for district heating may feature differences in reactor and building design due to their lower operating pressure and temperature than existing NPPs.

- New types of reactors and related material issues (SMRs)
- Passive components, load following, operational conditions
- Structural integrity of new building materials and methods
- New containment solutions (and pool structures)

5.4.4.4 Additive manufacturing

An area of increasing interest is the use of additive manufacturing techniques to produce components for nuclear power plant applications. Additive manufacturing, or AM, also sometimes called 3D printing, is particularly suitable for efficiently fabricating objects with complex geometries. The material alternatives are rapidly expanding, and include a variety of steels, stainless steels and nickel-based alloys relevant to the nuclear industry. AM has a much longer history in non-nuclear sectors, such as automobile manufacturing, but it is gaining increasing interest in other safety-conscious industries, such as aerospace. As spare parts for operating nuclear power plants become scarce due to loss of the original supply chains, additive manufacturing is seen as a potential alternative route for securing the necessary components. There may also be applications in complex component geometries, or even in more 'standard' use in future reactors such as SMRs.

When it comes to employing AM components in a nuclear power plant, the most important issue from a safety standpoint is qualification of the fabricated component. In comparison to conventionally-manufactured components, those fabricated by AM require special attention to three particular aspects: the material properties, the structural integrity, and the inspectability of the resulting component. The material properties of AM components are particularly subject to anisotropy, porosity, thermal effects from the fabrication process, and post-treatments such as heat treatment and hot isostatic pressing. The basic material properties form the foundation for their structural integrity in use as components of particular geometries. The anisotropy and porosity that may develop in AM materials can also impact the non-destructive testing response, making inspections before and during the operating lifetime difficult if they are not properly accounted for. The assessment of AM components for qualification relies on standardised mechanical testing, but may also require the assessment of microstructures, as well as more sophisticated testing such as stress corrosion cracking tests, and testing following neutron irradiation, higher temperatures, etc.

From a competence-building perspective, currently many experts in Finland are familiar with the methods employed in qualifying materials for use in nuclear power plants, and the response of conventionally-manufactured materials to such tests. However, only some people have experience of the special aspects of AM, and the relative importance of various fabrication and post-processing parameters. In particular, the response of AM components to more complex environments such as NPP water chemistry and neutron irradiation are as yet largely unknown. For that reason, research is needed to 1) familiarise materials experts with the strengths and weaknesses of various AM materials, and the effects of fabrication and post-fabrication processing, 2) better understand the NDE response of AM components, and 3) better understand the response of AM materials to exposure in the long term to plant environments, neutron irradiation, elevated temperatures and combinations thereof, for ageing management purposes.

5.4.5 Safety-related relevant loads

5.4.5.1 Fragilities

The determination of fragility curve is an important and practical measuring tool between safety-related relevant loads and the corresponding capacity of identified safety-related systems structures and components (SSCs). Discussion of fragilities include at least the following points of view. At first fragility curves are used to understand dependencies between hazards/threats and capacities of SSCs. This includes a common understanding of the overall safety of NPP, where systems and components receive loads via building foundations and frameworks. Therefore, the fragility curve may even have to include analytical studies with corresponding assessment of boundary conditions between the hazard/threat and structural system of SSC.

Another point of view is to take a closer look at the design criteria itself, to understand the design basis and design extension conditions of hazard/threat against the corresponding SSC, which form a defence-in-depth of the NPP, and fragility measures the corresponding safety margins in design. This could strengthen the common understanding of how the standard-based design margin supports the corresponding safety goals, where standards-based material and the structural criteria of stress-strain capacities are not directly meeting safety goals based on leak tightness, etc. Corresponding international testing-based research is ongoing to measure and study the correlation between safety criteria and standards-based material and structural criteria. Some international case studies presented in OECD/NEA could support the fragility research in practice.

Nonlinear analysis and applications are needed, especially for assessing design extension conditions with higher parts of the fragilities estimated. The continuity of the fragility curve and avoiding cliff-edge effects often require nonlinear analysis both from the material specifications and structural stability points of view, for example.

In common with methodology and analysis tools for fragility research, special loads related to the safety of NPPs also require more study. Special attention should be paid to load cases caused by aeroplane crashes, explosions and missiles, since they are not commonly studied within conventional construction. There is valuable international cooperation going on in IAEA and OECD for ensuring NPP safety against special loads. To get the benefits from this high-level methodology and analysis tool benchmarking, extensive domestic research is needed.

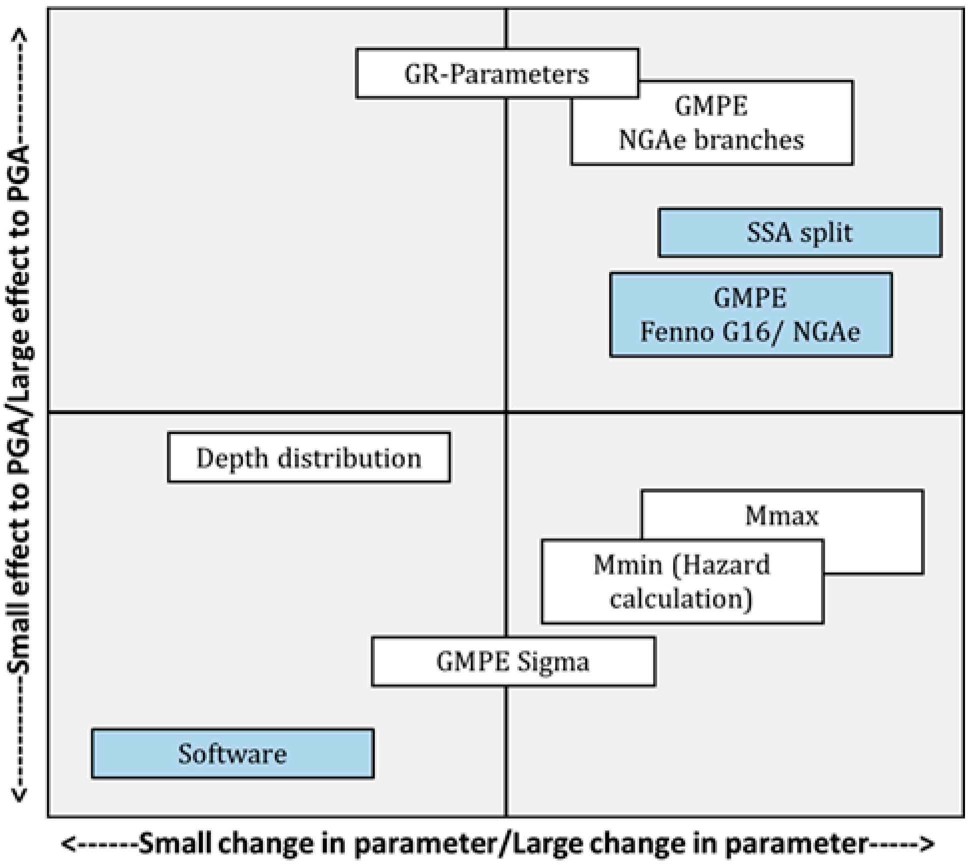
Common industrial development is unintentionally leading to new kinds of threats, which should be followed up as a common physical phenomenon from an NPP safety point of view. Corresponding follow-up and awareness also requires research. The hydrogen economy is looming in the future. There have already been preliminarily studies into the safety distance of an electrolysis facility located in the vicinity of an NPP. The reliability of the assessments carried out could be analysed further. Research could be expanded into what types of structures could be used to protect the NPP from a potential explosion hazard and how the mentioned structures affect required safety distances.

5.4.5.2 Seismic hazards

Seismicity, seismic hazards and risks have been studied from the NPP seismic safety point of view in Finland since the 1980s. Due to low seismicity, seismic hazard estimation and earthquake engineering for current design basis and design extension conditions are still challenging. There are no seismic design requirements for other buildings and facilities than NPPs. Therefore, there has been only limited interest in seismic hazard analysis outside the nuclear energy field. A lot of efforts have been used for understanding the nature of seismic hazard assessment between areas on different levels of seismicity.

In Finland, a traditional estimate for design basis earthquake criteria for NPP is based on the median curve of seismic hazard in AFE 10-5/a. The corresponding design extension condition is based on the medium curve, about AFE 10-7/a. Compared to the situation in Finland, the latest seismic hazard estimations based on larger data collection seismic hazard assessments use mean hazard curves instead of median hazards. The possible transition from median to mean curve should also be researched in Finland. A comparison between medium hazard and mean hazard curves also require research into corresponding AFE values. More research is needed for strengthening the consensus for applying Gutenberg-Richter (G-R) parameters on common and seismic source area (SSA) basis seismicity and the use of internationally approved ground motion prediction equations (GMPEs) in Finnish hazard studies. For example, ensuring internationally approved GMPEs require kappa comparisons between Finnish and other bedrock areas. This should be verified with commonly approved scientific publications based on measurements and analysis. Figure 5.3 below illustrates how different level variations of seismicity parameters could affect peak ground acceleration (PGA) estimations.

Figure. 5.3. Effects on PGA of different items in Sensei project



5.4.5.3 Fire safety engineering

Fire hazards still constitute a significant part of the risk profile of NPPs. Research should continue to look at the development and validation of analysis tools. This work sustains high knowledge levels and capabilities to perform fire safety assessments when needed by stakeholders. Research topics such as the modelling of ignitions have surfaced recently. The early development of fires could be better understood to correctly assess risks and identify when an ignition will lead to fully grown fire. Stakeholders also have some interest in the following topics related to fire hazards: multi-room fire scenarios, effects of ventilation on compartment fires, and battery fires. These topics are closely associated with overall plant safety. The robustness of corresponding safety cases could be assessed via fragilities of systems, structures and components (SSC) related to fire conditions.

Fire stops of penetrating cables and pipes are essential for maintaining robust fire compartmentation. Fire stops are a possible topic of research as the fire resistance rating of a fire stop often has to be justified via expert statements instead of classification based on experimental data and standards. The effects of ageing of cables on their fire properties have been studied, but research needs still exist. Such research could also be expanded into fire stops.

5.4.5.4 Validation and development of methods and tools

Although computational methods, e.g. finite element analysis, has been in use for many years, new elements meshing algorithms, numerical algorithms and especially material models are constantly developing. In order to ensure reliability of computational results, calculation methods and tools should be validated. According to a very famous definition, validation is supposed to substantiate 'that a computerised model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model' (Schlesinger et al. 1979). Validation is concerned with the accuracy of the model and looks at how well it captures the physical behaviour of the real-world situation it is meant to simulate. Any model will be, even at its best, an approximation of the actual physical system. In that context, validation focuses on the goal of the simulation and asks if the simulation meets the conditions for acceptance.

Validation against experimental data is the best option, but the challenge lies in finding useful test data. Since most of the tests are expensive to carry out, well-documented test data cannot necessarily be obtained in the open literature. In the case test, results are clearly presented, but all the necessary information needed for the input data is not always properly documented. Material test data obtained with sophisticated measurement techniques is needed for validating developed material models.

Participation in a benchmark calculation project is often a cost-effective way of getting calculation methods and tools validated. The organiser provides properly documented, high-quality data. Additionally, the workshops organised at different stages of the benchmark project give opportunities to contact other experts working on the same subject. Additional benefits are a common learning process, useful contacts, discussions, and exchange of user experiences on different kinds of computational methods. Also, capabilities of other corresponding computational methods and codes can be easily gathered. The OECD is continuously organising benchmark projects dedicated to NPP applications. Participation in OECD/NEA large-scale experimental activities and related benchmark exercises enables continuous code assessment and aids in identifying code development needs for fire dynamics simulation (FDS), for example. The OECD/NEA experimental programmes related to fire will continue and Finnish participation is encouraged.

Computational analysis methods and tools for impact-loaded reinforced concrete structure analyses have been developed and validated utilising the data and observations obtained from the impact tests carried out at VTT since 2006. These tests were carried out using a target slab of 2m x 2m. Now there is a clear need to study the so-called scaling effect and thus validate the calculation methods and tools with test results obtained from larger scale tests.

There is also a clear need to validate the capabilities of existing calculation methods for the analysis of steel-concrete-steel structures as well as shear walls under impact and seismic loading conditions, and further to define development needs. Analysis methods for these purposes should be developed further.

5.4.6 International collaboration

International collaboration in the mechanical and structural safety of NPPs should take the form of active participation in key international programmes, conferences, working groups and topical forums, and bringing the important messages back to Finnish stakeholders. In addition to the valuable research results that can be collected through participation in such forums, written travel/summary reports from such events that are then shared within the domestic nuclear community are an important means of extracting domestic value from international collaborations. In the mechanical and structural safety of NPPs, there are ongoing IAEA and OECD NEA programmes and projects regarding many aspects of materials ageing, ranging from reactor pressure vessel integrity to internals materials, and from concrete civil structures to polymers and cables. The Electric Power Research Institute also organises many specific forums around particular topics, such as irradiation-assisted stress corrosion cracking, Ni-based alloys, water chemistry and other topics important to long-term operation, including concrete infrastructure and VVERs. Simultaneously, there are activities regarding newer topics such as small modular reactors and additive manufacturing. Whether through community-level organisations such as IAEA, OECD or industry-oriented ones such as EPRI-organised forums, participation in them generally requires some contributions from the participants, either financial or in-kind. Such collaborations have been valuable for the domestic nuclear community, so SAFER projects should consider being structured to enable participation on a results-sharing basis in international forums. Important open industry conferences such as the French-organised Fontevraud series 'Contribution of Materials Investigations and Operating Experience to LWRs' Safety, Performance and Reliability', and the US-organised series 'Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors' generally feature topics of direct importance to the mechanical and structural safety of NPPs, where results can be shared and also collected, and the important human connections can be forged between experts. Likewise, closed forums such as the International Cooperative Group on Environmentally Assisted Cracking (IGC-EAC), the International Group on Radiation Damage Mechanisms (IGRDM), and the International Committee in Irradiated Concrete (ICIC), that collect the top world experts with the latest, often as yet unpublished, information on the degradation of primary and secondary circuit materials, reactor pressure vessels and irradiated concrete. Access to such groups is generally contingent on participants sharing the latest research results, and thus can be an important aspect to include in a SAFER2028 project. Finally, although not yet in operation, the Jules Horowitz materials test reactor is set to be an important focal point for international collaboration going forward, now that the OECD Halden Reactor Project is being wound down. In the interim, the OECD NEA Framework for Irradiation Experiments (FIDES) programme is getting underway as an important international collaborative forum for nuclear materials testing.

International collaboration in joint projects can also be considered, particularly in the spirit of projects such as BRUTE, in which harvested material from the decommissioned Barsebäck power plant are tested in collaboration with Swedish participants. The SMILE programme is another international collaborative project utilising materials harvested from decommissioned Swedish power plants, and features many primary and secondary circuit materials and their degradation. The NKS forum also provides complementary funding that can promote Nordic collaboration within SAFER2028 projects. Collaboration in EURATOM projects has the potential to draw on a much broader resource base, and benefit from a much larger pool of research results, which in turn can inform the research activities within SAFER2028 projects. In the 2021 EURATOM funding round, project proposals included many projects with the same topics identified as important for the mechanical and structural safety of NPPs in SAFER2028. Even without direct funding collaborations between SAFER2028 and EURATOM, complementarity between projects can be mutually beneficial from the perspective of building national competencies in topics important to the mechanical and structural safety of NPPs.

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