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National Nuclear Power Plant Safety Research 2019–2022

SAFIR2022 Framework Plan

Ministry of Economic Affairs
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Abstract

The public nuclear safety research programmes provide the necessary conditions for maintaining the knowledge needed for ensuring the continuance of safe and economical use of nuclear power, for the development of new know-how and for participation in international cooperation. The Finnish organisations engaged in research in this sector have been an important resource that the various ministries, the Radiation and Nuclear Safety Authority (STUK) and the power companies have had at their disposal.

The Ministry of Economic Affairs and Employment (MEAE) appointed in November 2017 a group to write the Framework Plan for the new programme. This report contains a proposal for the general outline of the programme, entitled SAFIR2022 (SAfety of Nuclear Power Plants – FInnish National Research Programme). The plan has been prepared for the period 2019–2022, but it is based on safety challenges identified for a longer time span as well. The research programme is strongly based on Chapter 7a of the Finnish Nuclear Energy Act.

The construction and planning of new power plant units have increased the need for experts. At the same time, the retirement of existing experts has taken place and retirements are continuing. Active long-term research still plays a key role in the education and training of new experts.

The Framework Plan aims to define the important research needs related to safety challenges. The programme also aims to maintain and increase know-how in those areas where no significant changes occur but in which research activities are the precondition for the safe use of nuclear power.

MEAE contact: Energy Department/Jorma Aurela, tel. +358 50 5922109

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Referat

Av ett land som använder kärnenergi krävs en tillräcklig infrastruktur, som täcker såväl anläggningarnas drifts- och myndighetstillsynsorganisationer som utbildningen och forskningen i branschen. Principen för de offentliga programmen för forskning i kärnsäkerhet är att de skapar förutsättningar för att bevara den kunskap som behövs för att en säker och ekonomisk användning av kärnkraften skall kunna fortgå, för att utveckla ny kunskap och för att delta i internationellt samarbete. De organisationer som bedriver forskning inom sektorn i Finland har följaktligen varit en viktig resurs, som de olika ministerierna, Strålsäkerhetscentralen (STUK) och kraftbolagen har kunnat utnyttja också under det SAFIR-program som avslutas år 2018.

På uppdrag av handels- och industriministeriet utnämndes i November 2017 en grupp, som fick till huvuduppgift att planera innehållet i ett nytt program. I denna rapport finns ett förslag till stomplan för detta program med arbetsnamnet SAFIR2022 (SAfety of nuclear power plants – FInnish national Research programme). Planen har gjorts för åren 2019–2022, men den grundar sig också på utmaningar för säkerheten som har identifierats för en längre tid. Vid planeringen har byggnadsprojektet kärnkraftverket Olkiluoto 3 och Hanhikivi 1 projektet i hög grad beaktas. De utmaningar som de gamla och den nya anläggningen innebär för säkerheten och de forskningsbehov som följer av detta är emellertid till största delen samstämmiga. Stomplanen grundar sig på kapitel 7 a i kärnenergilagen, vilket trädde i kraft år 2004.

Byggandet av nya anläggningarna ökar behovet av sakkunniga inom denna sektor i Finland. Samtidigt går också allt flera av de nuvarande sakkunniga i pension. Tillsammans ökar dessa två faktorer behovet av utbildning, och där är en aktiv forskningsverksamhet av väsentlig betydelse. Situationen medför också en stor utmaning då det gäller att upprätthålla säkerhetsforskningen på lång sikt.

Kontaktperson på ANM: Energiavdelningen/ Jorma Aurela, tfn 050 5922109

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Tiivistelmä

Ydinenergiaa käyttävältä maalta edellytetään riittävää infrastruktuuria, joka kattaa ydinlaitosten käyttö- ja viranomaisvalvontaorganisaatioiden lisäksi myös alan koulutuksen ja tutkimuksen. 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) ja voimayhtiöt ovat pystyneet hyödyntämään myös 2018 päättyvän SAFIR2018-ohjelman aikana.

Työ- ja elinkeinoministeriön toimeksianto nimesi marraskuussa 2017 ryhmän, jonka päätehtävänä oli suunnitella uuden ohjelman sisältö. Tässä raportissa on ehdotus tämän työnimellä SAFIR2022 (SAfety of Nuclear Power Plants – Finnish National Research Programme) kulkevan ohjelman runkosuunnitelmaksi. Suunnitelma on tehty vuosille 2019–2022, mutta se perustuu myös pidemmälle aikajänteelle tunnistettuihin turvallisuushaasteisiin. Suunnittelussa on otettu huomioon Olkiluoto 3 -ydinvoimalaitosyksikkö ja Hanhikivi 1-hanke.Vanhojen ja uusien laitoksien asettamat turvallisuushaasteet ja tästä seuraavat tutkimustarpeet ovat kuitenkin suurimmalta osin yhtenevät. Runkosuunnitelma perustuu vuonna 2004 voimaan tulleeseen ydinenergialain lukuun 7a.

Uudet hankkeet lisäävät Suomessa alan asiantuntijoiden tarvetta. Samaan aikaan myös nykyisten asiantuntijoiden eläkkeelle siirtyminen jatkuu. Nämä yhdessä lisäävät koulutustarvetta, missä aktiivisella tutkimustoiminnalla on oleellinen merkitys. Tilanne asettaa myös pitkäjänteisen turvallisuustutkimuksen ylläpidolle suuren haasteen.

TEM:n yhdyshenkilö: Energiaosasto/Jorma Aurela, puh. (050) 5922109

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PREFACE

When nuclear technology was being implemented in Finland in the 1960s and 1970s, the significance of research in creating and developing know-how regarding nuclear safety was already clear. Finland's capacity for decision-making – independent of the suppliers of nuclear power plants and safety assessments – has been developed systematically in national nuclear safety research programmes since the beginning of the 1990s. The research programme now under preparation is the fifth to cover the various areas of competence of the safety research of nuclear power plants.

The planning of the new nuclear safety research programme considers the changes in the operating environment reflecting the changes in the energy system in Finland and the global framework. Planning is guided by the research strategy for the nuclear power sector, covering the period up to 2030, prepared under the supervision of the Ministry of Economy Affairs and Employment (MEAE). The national research strategy strongly emphasises the significance of national programmes and sets new goals for increasing the scientific level of research and its internationalisation. The significance of sufficient resources and of the applicable infrastructure is also presented. The strategy emphasises the importance of European research for Finland and the need to develop business from the research.

The national nuclear power plant safety research programme SAFIR2018 is the largest national research programme and a significant factor in the field. The SAFIR2018 research programme has received international recognition both in the evaluation of the programme and in connection with the handling of the Convention on Nuclear Safety. The renewal of the nuclear safety research infrastructure has proceeded well and valuable assets have been developed to enable high-level nuclear safety research in Finland. Earlier results of the research programme, a solid Framework Plan with interesting research topics and high-quality results, are important for co-operation with new international partners.

The MEAE started preparing the Framework Plan for the new national nuclear power plant safety research programme in November 2017. The programme's planning group has included representatives from all key organisations participating in nuclear safety work along with experts in the field so that 17 people in total have been involved in preparing this new programme with the support of numerous experts in different stakeholder organisations.

Continuous improvement and systematic building of capability for solving nuclear safety issues relevant to Finnish nuclear power plants have been the driving forces behind the planning of the new research programme. Research creates expertise and vigilance in identifying safety issues. Competence resides primarily in people, but also in infrastructure, such as laboratories and computational software, educational and training organisations, national and international networks of cooperation and government and industry more broadly. In the planning work, the working group has accepted the challenge and, as a result, programme level goals for 2022 and even for 2026 have been set for eight overarching topical areas. Shared topics of interest with the national nuclear waste management research programme KYT2022 have been identified and enhanced co-operation between the programmes is expected during the next programme period.

The management of overall safety and strong emphasis on the principles of defence in depth, not only in design but also at the national institutional level, call for multidisciplinary projects. As new topics, the safety and security interfaces and insight of the changes in the energy systems and operating environment open up new challenging research issues. Further enhancement of the programme and an even more ambitious goal for the research programme are well justified due to ongoing major investments.

The planning group has been engaged to further enhance national nuclear safety research in Finland and brought new insight to the programme. Enthusiastic and multidisciplinary discussions on nuclear safety research took place during the work. The preparation process has produced a solid and interesting research entity, which is one tangible step towards the implementation of the research strategy for the nuclear power sector. The preparation work of the Framework Plan has created a solid foundation for the new SAFIR2022 research programme and beyond.

Marja-Leena Järvinen
Chairman of the working group

1 Introduction

The Ministry of Economic Affairs and Employment (MEAE) is initiating a four-year national technical and scientific research programme on the safety of nuclear power plants for the years 2019 and 2022. The new programme is a continuation in the series of government-led nuclear safety programmes that have proven their value in maintaining and developing expertise. The safety research programme is based on Chapter 7a ("Ensuring availability of expertise") of the Finnish Nuclear Energy Act. In essence, the programme covers the themes of the SAFIR2018 programme that will end in 2018 [1, 2]. The programme is funded by the Finnish State Nuclear Waste Management Fund (VYR), as well as other key organisations operating in the area of nuclear energy. The annual funding of the SAFIR2018 programme has been approximately EUR 10 million per year. During the new programme period, development of national nuclear safety research infrastructures still requires a major share in the VYR funding. The new programme also aims at funding used for research to remain constant or to increase slightly from SAFIR2018. The abbreviation SAFIR2022 is used for the new research programme.

In parallel to the SAFIR2022 programme, the MEAE is continuing the annual VYR funding for VTT Centre for Nuclear Safety (infrastructure investments until 2020 and laboratory rents). The MEAE proposes funding for the VYR in connection with the rest of the project entity in conformance with Chapter 7a of the Nuclear Energy Act.

The planning period for the national research programme on nuclear power plant safety up to 2022 involves several licencing phases for new and existing power plants: the periodic safety review for Loviisa 1 and 2 is due in 2023, operation of Olkiluoto 3 is about to start, and the construction licence application for Hanhikivi 1 is under evaluation. An operating licence application for building a final disposal facility for spent nuclear fuel will be prepared. These processes are reflected in many ways in national safety research. The renewal of the operating license for Olkiluoto

1 and 2 to extend the lifetime to 60 years is under government review at the time of writing this Framework Plan. Expertise developed in publicly funded research programmes is applied to the licensing processes.

As new plant projects advance, more expert resources are needed. New projects have increased international interest in nuclear safety work and research carried out in this area in Finland. The construction of the new unit and other new projects have also increased the attractiveness of the field, which is reflected in students' interest in the field, as well as in the number of applications for vacant positions.

Research in nuclear safety requires comprehensive training and commitment. The research programme serves as an important environment providing long-term activity, which is especially important now that the research community is facing a generation change. A new generation of researchers has to be recruited and engaged. The international evaluation of the current research programme [3] stated that the research by VTT, Lappeenranta University of Technology (LUT) and other involved research organisations is meeting very high standards. Maintaining this kind of activity across different organisations in today's world is a challenge.

The licensing processes and the possibility of recruiting new personnel for safety-related research projects provide an opportunity for experts of different ages to work together, facilitating the transfer of knowledge between generations. This ensures that the available experience of running nuclear power plants is exploited in the best possible manner.

Globalisation and networking highlight the importance of national safety research. This creates pressure to unify nuclear safety requirements and supervision procedures. Currently, there are many projects related to national regulations and international safety requirements and guidelines. The directive amending the Nuclear Safety Directive was published in 2014 and it is now implemented in national law. A country such as Finland also has to be very active in international nuclear safety programmes, such as the IAEA, OECD NEA, Euratom Programmes, the JHR community and the NKS research.

The MEAE and the Finnish State Nuclear Waste Management Fund (VYR) appointed the administrative organisation and director to the new research programme on the basis of a public tendering process in March 2018, and in 2017 appointed the members to the working group from representatives of central organisations taking part in nuclear safety work [6]. The objective of the working group was to produce the Framework Plan for the research programme, as well as a proposal for its organisation.

The working group has supplemented its expertise by consulting experts, and approximately 70 professionals from different organisations have taken part in the planning. During the process, the working group was subdivided into three separate teams that will also form the fields of research of the SAFIR2022 programme. As part of the planning process, a SAFIR2022 workshop was held in April 2018 in Otaniemi, with 70 attending delegates. The group assignments for the seminar, which the teams have since developed further, have made a great contribution to creating the Framework Plan.

The international evaluation of the SAFIR2018 programme ordered by the MEAE, whose final report was published in May 2018 [3], has also provided valuable input into the planning process. The evaluation panel's recommendations for the next programme were:

1. Develop a strategic roadmap
2. Consider flexible funding to support diverse projects and more new initiatives
3. Consider flexible organising to build a vibrant research community
4. Develop ways to assess impact
5. Think of organisational change as a collaborative opportunity.

The evaluation panel's recommendations were taken into account in the SAFIR2022 Framework Plan. They will also be applied to future project proposals and the forthcoming operational management handbook revision.

The Finnish National Research Programme on the Safety of Nuclear Power Plants SAFIR2022 will begin with a public call for research proposals in August 2018. The MEAE will appoint the Management Board for the new research programme in summer 2018. The programme will start at the beginning of 2019.

This document presents a proposal for the organisation of the programme, describes the operating environment, and elaborates on the research areas of SAFIR2022 and on their needs for research. The research areas and needs are based on the knowledge available at the time the Framework Plan is drafted. The research programme takes into account possible changes in the operating environment and, if new challenges manifest themselves, new research topics supporting the objectives of the programme can be included.

2 Organisation of the Research Programme

2.1 Purpose of the programme and societal impact goals

In accordance with Chapter 7a of the Finnish Nuclear Energy Act, which was enacted in 2004, the objective of the SAFIR2018 research programme is to ensure that "should such new factors concerning safe operation of nuclear facilities emerge that could not be foreseen, the authorities have such sufficient and comprehensive nuclear engineering expertise and other facilities at their disposal that can be used, when necessary, to analyse without delay the significance of such factors". High scientific quality for the research projects is required in the programme. Their results must be available for publication.

Bearing in mind the continuous improvement, the programme covers the themes of the SAFIR2018 programme that will end in 2018: 1) Plant safety and systemic approach to safety, 2) Reactor safety and 3) Structural safety and materials. In more detail, safety assessment capability is developed and created in human and organisation factors, nuclear safety I&C and electrical systems, fuel safety, thermal hydraulic methods, severe accidents assessment, primary coolant circuit, structures and research on probabilistic methods. The Fukushima Daiichi nuclear power plant accident caused by the 2011 earthquake and the subsequent tsunami in Japan resulted in an increase in the volume of research in such areas as extreme external hazards and accident management. While previously mentioned research topics are well covered in the programme, there is room for improvement in the research of the interfaces for safety and security. This emerging topic needs new research although the public nature of the programme and sensitivity of the research topic limit the scope of research.

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 constructing new capacity that is planned for 60 years of operations. The systemic approach to safety and the roles of major actors such as the licensee, the Government and the regulator in building a national nuclear safety regime need to be understood. An integrated approach to safety, security, safeguards, society, standardisation and the sustainable use of nuclear energy highlights the need for vigilance. A strong safety culture is the driving force that enables the timely identification of safety issues, their assessment and the implementation of safety improvements.

The new programme also aims to maintain constant funding for research or to raise funding slightly from the SAFIR2018 level. The goal is to increase the size of the programme by obtaining more international funding and jointly funded projects. Nuclear safety research including competitive projects and the development of infrastructure is expected to be maintained at an elevated level throughout the programme period along with the development of the national infrastructure needed for nuclear safety research. The VTT Centre for Nuclear Safety will be completed and actual research at the new facility will commence. The focus of the infrastructure development programme will shift to the thermal hydraulic experimental facilities at Lappeenranta University of Technology. The international Jules Horowitz research reactor is expected to be commissioned before the end of this programme period in 2022.

The new programme SAFIR2022 continues its close cooperation with the national nuclear waste management programme KYT2022 funded by VYR. Overall safety, plant and fuel lifetime management, social issues and the development of nuclear safety research infrastructure are common topics for both research programmes.

The research programme will develop and create national nuclear safety assessment capability for solving future safety issues, international jointly funded research in nuclear specific areas and networking. The SAFIR2022 programme's planning group defined the following as the mission for national nuclear safety programmes:

> *"National nuclear safety research aims at high national nuclear safety assessment capability. It develops and creates expertise, experimental facilities as well as computational and assessment methods for solving future safety issues in close cooperation with competent international partners."*

The vision of SAFIR2022 was defined as follows:

> *"The SAFIR2022 research community is a vigilant, internationally recognised and strongly networked competence pool that carries out research on topics relevant to the safety of Finnish nuclear power plants on a high scientific level and with modern methods and experimental facilities."*

The funding of the programme is focused on the core themes, which are nuclear specific areas such as reactor safety and the integrity of the reactor pressure vessel, primary circuit and containment. In nuclear safety related areas, co-operation is sought with research institutes and organisations that possess excellence in the topical area. However, in the SAFIR2022 programme the application of research and nuclear safety aspects are the focus.

The SAFIR2022 Nuclear Safety Assessment Capability Model has been established and the following areas are looked at when assessing the development and creation of the national nuclear safety assessment capability for solving future safety issues: 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 overarching goal for the programme and the following programme period until 2026 are presented in Section 3.2.

2.2 Starting the programme

In November 2017, 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, as well as a proposal for its organisation. The working group was authorised when necessary to supplement its expertise by consulting permanent or temporary experts.

The working group, consisting of 15 members and a secretary, started its work in November 2017. The working group has supplemented its expertise by consulting experts and professionals from different organisations. The working group assembled and worked as a single body, but three groups were formed to write up proposals, one for each research area of the coming programme, along with a fourth group to discuss the management structure and general topics. As a part of the planning process, a workshop was held in Innopoli, with 70 delegates in attendance. The work of the workshop groups laid the foundation for the content of the Framework Plan. The new research programme spans four years from the beginning of 2019. The MEAE will appoint the Management Board of the new research programme and will publish the call for proposals for the 2019 research projects in August 2018.

In January 2018, 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 March 2018.

2.3 Programme administration

The programme's operating model consists of a Management Board and four research area steering groups working under its supervision, as well as reference groups 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 Programme Director, which have been appointed on the basis of the competitive bidding.

The research areas of the SAFIR2022 programme are:

- Plant safety and systemic approach to safety
- Reactor safety
- Structural safety and materials
- Research infrastructure

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 reference group assigned by the steering group for the research area.

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

The MEAE will appoint a Management Board for the programme that includes representatives of central nuclear safety organisations. The Management Board will nominate the research area steering groups and reference groups. The Management Board also appoints the chairpersons and members of the steering and reference groups. A reference group will be appointed in the SAFIR2018 programme for the development of research infrastructure

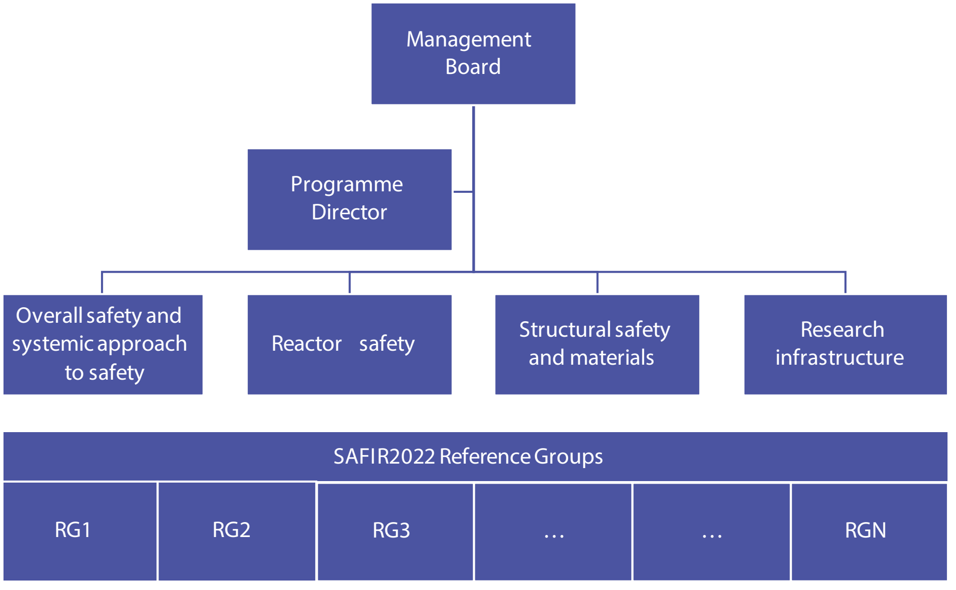
2.3.1 Management Board

The Management Board is responsible for the programme as a whole and its results so that the programme meets the statutory requirements. The Management Board 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 Management Board 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 of the Management Board is appointed from the Radiation and Nuclear Safety Authority (STUK) and the director of the programme acts as the secretary. One representative from each power company in the nuclear energy sector will be selected for the Management Board, along with a representative from every significant research institution and university carrying out nuclear research or education, and a representative from the Ministry of Economic Affairs and Employment (MEAE). The MEAE contact person will also serve as the Finnish State Nuclear Waste Management Fund (VYR) contact person. A deputy member will be appointed for each member. The Management Board's mandate will end on 31 March 2023. The participating organisations will cover the participation expenses of their representatives.

The Management Board defines the research area steering groups and reference groups. The Management Board also appoints the chairpersons, vice chairpersons and members of the steering and reference groups on the basis of proposals made by their organisations.

Figure 2.1 Structure of the programme's administration. Each project belongs to one reference group and its topic may be related to one or several research areas. The reference groups of the SAFIR2022 programme will be defined once the programme has started.



The Management Board will meet when needed and, as a general rule, three times a year (March, June, December).

The decisions of the Management Board will be recorded in the meeting minutes, which will be distributed to the organisations taking part in the SAFIR2022 programme.

2.3.2 Research area steering groups

The research area steering groups are responsible for the content and results of the research programme in their respective fields; they prepare the calls for proposals for their fields, evaluate research project proposals and place the projects in the reference groups. 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. A steering group can propose the establishment of new reference groups in its own area and also propose multidisciplinary groups to the Management Board.

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

The chair of a steering group for an area is appointed from STUK and the director of the programme acts as the secretary. One representative from each power company in the nuclear energy sector will be appointed to a steering group. A deputy member will be appointed for each steering group member.

The steering groups will meet when needed and, as a general rule, three times a year (March, May, November). The results of the research projects of the preceding year and the updated project plans of the starting year will be assessed in the March meeting. The proposals for the next year are evaluated in the November meeting.

The decisions of a steering group and its proposals for the Management Board will be documented in the minutes distributed to the management group, reference groups and the project managers involved.

2.3.3 Reference groups

The reference groups are responsible for the scientific and technological guidance of the research. 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 reference groups may evaluate the scientific level and content of the research project proposals upon request of the steering group of the research area.

The Management Board will confirm the research topics and composition of each reference group on the basis of the proposal of the steering group of the research area. New reference groups can be set up and old ones terminated during the programme.

The chairperson of a reference group is a representative of a nuclear energy company 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 reference group so that each company in the nuclear energy sector, 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. Deputy members may be appointed for each organisation represented.

Minutes are prepared of the meetings of the reference groups, in which any decisions concerning the content of the projects and the proposals to be made to the steering or management groups will be documented. The minutes will be distributed to the Management Board, the research area steering groups and the project managers in question. The reference group will meet when needed and, as a general rule, three times a year (February, May, October).

2.3.4 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 and separate annual orders and appended offers for each year.
A project coordinator assists the Programme Director in the administration and acts as a substitute in 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 Management Board and implement its decisions, maintain the programme's website and 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 steering group meetings and see to the co-ordination between reference groups 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 of the projects, assessed by the reference groups, for the steering group meetings in order to assist the approval of the invoicing. The Programme Director participates in the meetings of the Management Board, steering groups and the reference groups.

The director and the administrative organisation prepare the annual plan for the programme, the annual report and other required reports and follow up 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 Management Board.

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 Management Board, 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.

2.3.5 Project manager, research group and research execution organisation

Research projects are led by a project manager who also participates in research activities together with other researchers in the project. The project manager and the organisation the manager represents are responsible for executing the project according to the project plan and the budget, and according to the decisions of the steering group of the research area. The project manager is responsible for the realisation of the whole project and leads the communication within the project's research group, other projects, the reference group guiding the project and the programme management. The project manager is responsible for the reporting obligations set for the project in the programme.

Ad hoc project meetings with participants from the organisations with members in the related reference group should be organised as often as needed and their main findings should be reported in the reference group meetings. The ad hoc meetings may be project-specific but also informal meetings with several projects dealing with the same research topic are encouraged.

2.4 Project portfolio and procedure for calls for proposals

The research projects in the programme shall have ambitious goals and be of high quality by international standards. The project objectives can be application-oriented or they can develop and maintain basic competence recognised as important in the Framework Plan. Applied projects can create new scientific results or bring known results into practical use in a new way. Projects that develop and maintain basic competence ensure that Finland has the necessary expertise, validated methods and experimental facilities for the safe use of nuclear power.

The project plans should demonstrate the novelty of the research, show how the project will strengthen Finnish competence 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 suitable research topics. Doctoral theses demonstrate the qualifications of the researchers and the scientific novelty of the findings. However, in addition to these, the work must also be significant to the research programme.

Clear goals and tasks must be set for each project funded in the programme. The steering groups must 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 the project year in January.

A call for proposals will be announced annually in early autumn regarding projects proposed for funding by VYR. Project proposals can be made for one or several years. If funding is granted for a project longer than one year, further funding will generally be granted for it according to the project plan. However, the Management Board may propose to the MEAE and VYR that the 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.

In addition to actual research projects, the SAFIR2022 Management Board can annually initiate small studies with the order procedure. Decisions on the 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 actual research projects. They can also introduce new topics.

The Management Board will annually reserve a certain proportion of the available VYR funding for one- or two-year research projects and small studies. New innovative topics with bigger risks are recommended to be started as one- or two-year projects. The longer projects shall focus on competencies that have already been recognised as important for nuclear safety in Finland. Doctoral theses can be included as parts of the longer projects.

The selection criteria for project proposals to be funded are the projects' ability to develop expertise, methods, experimental facilities and networking in the field. In particular, the implementation of the requirement of Chapter 7a of the Nuclear Energy Act will receive special attention. The requirement is to ensure that the authorities 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 steering groups of the research areas in the SAFIR2022 programme assess the project proposals, and the programme's Management Board will make an annual proposal to the MEAE on the research projects to be funded. The MEAE will make a proposal to VYR of 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 projects' competitive situation may change. The management group may also propose a multi-year project is terminated. The selection procedure for research projects will be described in detail in the research programme's operational management guide.

During the project evaluation phase, the Management Board has the possibility of negotiating with the parties proposing projects and with the funders on changing the goals and funding, and on combining project proposals into larger entities. It is also possible to propose projects for the research programme for which funding is not applied from VYR. The management group 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 the participation fees related to international treaties, 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% indirect employee costs ("henkilösivukulut") and 30% 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.

2.5 Results of the research programme

The main purpose of the research programme is to enhance the Finnish nuclear safety assessment capability for solving future safety issues as they appear. This capability is assessed against the goal set in the Nuclear Energy Act, Section 53, and more detailed using the SAFIR Nuclear Safety Assessment Capability Model presented in Appendix 1. 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 and training and networking, 5) knowledge management and assets and 6) general research programme indicators.

The goals for the SAFIR2022 programme and beyond until 2026 are presented under eight topics. All of the research projects funded develop or create nuclear safety assessment capability building in Finland. The overarching topics express more specific goals for the programme period. The list below presents the overarching research topics for which the milestones are presented in Section 3.2.

1. Nuclear safety assessment capability building
2. Overall safety and systemic approach to safety
3. Validated tools for reactor and nuclear power plant analysis
4. Nuclear fuel and its lifecycle from reactor to final disposal
5. Ageing phenomena and the integrity of barriers
6. Severe accidents
7. External hazards
8. Nuclear safety in a changing environment

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

2.6 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.

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 for 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 appointed and the Programme Director are responsible for the administration of the programme. The responsibilities of the administrative organisation are defined in the order and the financing terms of the administrative project.

All VYR-funded projects shall provide their Finnish participants and the SAFIR2022 organisations with access to the research results.

2.7 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 a deep level of competence requires postgraduate studies and a doctoral thesis. The numbers of doctoral and other theses are important result indicators of the SAFIR2022 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 Management Board, in the steering groups and the reference groups 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.

2.8 Co-operation with nuclear energy research and doctoral training programmes in Finland

Nuclear energy research in Finland is divided among diverse organisations. Most of the publicly funded research and development is conducted at the Technical Research Centre of Finland Ltd (VTT). Other major research institutions are Aalto University, Lappeenranta University of Technology (LUT), the Geological Survey of Finland (GTK), the Finnish Meteorological Institute and the universities of Helsinki, Oulu, Eastern Finland and Jyväskylä, the Tampere University of Technology and the Finnish Institute of Occupational Health. In addition, STUK, Fortum, Teollisuuden Voima Oyj (TVO) and Posiva Oy have funded their own research and various projects conducted outside of Finland.

The total scope of nuclear energy research in Finland is approximately EUR 75 million annually. The most significant funders of the research are VYR, Business Finland, Euratom and occasionally the Academy of Finland. Other financers include VTT, STUK, universities, power companies, NKS and various EU funding channels.

More than half of the research funding has been applied to nuclear waste management research. Most of that is research funded by the owners of Posiva Oy, focusing on the safe disposal of nuclear waste. A major role is played by the ONKALO research facility in Olkiluoto. The Finnish Research Programme on Nuclear Waste Management KYT2018 (2015–2018) is implementing some of the technical and scientific projects of the previous programme phase, with the aim of reinforcing national competence. The objective is to develop and maintain the basic competence needed for carrying out the planned nuclear waste management solutions in Finland. The projects are divided into strategic analyses and projects that deal with the long-term safety of the geological disposal of spent fuel. The KYT2018 research projects involve VTT, GTK and several universities. The new research programme, KYT2022, is under preparation in conjunction with the preparation of SAFIR2022.

The SAFIR2018 nuclear safety research programme has accounted for approximately half of all the nuclear safety research in Finland by volume. Other nuclear safety research comprises projects funded exclusively or jointly by power companies, research institutions and universities. Research conducted by Fortum focuses on questions concerning Loviisa VVER-440-type plants—for instance, in relation to material ageing, thermal hydraulics, nuclear fuel, reactor technology and plant technology. TVO's research focuses on matters such as fuel and specific questions concerning the Olkiluoto 1 and 2 plant units and, in the future, also Olkiluoto 3. Fennovoima's future needs will be focused on technical solutions for the Hanhikivi 1 unit. VTT has conducted reactor safety research outside of SAFIR2018, particularly within Euratom projects. Other research funded by VTT includes research on next-generation reactors (GenIV) and the development of internal competence that cannot be included in national research programmes.

The Academy of Finland has funded nuclear technology-related research through a dedicated call and through its Sustainable Energy programme in the past. At present, the funding for basic research in this area is absent. National research collaboration has been strengthened, particularly between VTT, Aalto University and Lappeenranta University of Technology, by participating in infrastructure roadmap development.

The main aim of the Research Partnership in Fusion Energy (Euratom–Tekes association until 2013, from then on the EUROfusion Consortium) is to develop technology that interests Finnish industry for the ITER experimental reactor, and to participate in a carefully focused manner in fusion research being conducted in the EU alongside ITER. The research areas of the technology programme are fusion plasma research, plasma–wall interactions, fusion reactor material research, the development of superconductive wires, remote controlled maintenance systems and systemic studies. The focal points of Finnish fusion energy research are evaluated according to the focal points of the European Fusion Programme, which ensures maximum benefits for the product deliveries and competence development of Finnish companies.

In January 2013, the MEAE appointed a committee to prepare the research strategy for the nuclear energy field until 2030. The preparation was based on the report of the national competence working group on the nuclear energy field that finished its work in March 2012 [4]. The strategies were published in April 2014 [5]. Of the recommendations in the strategy, "The areas of focus of the nuclear energy research must be assembled into broad national programmes" touches the SAFIR2022 programme directly. The recommendation states that the basis for nuclear safety and nuclear waste management research is still comprised of the national research programmes in these areas. In addition, it is recommended that national research programmes for radiation safety research and future nuclear energy research (fission and fusion) should be set up.

Universities, research institutions, authorities and the industry must be committed to supporting a multi-sector and multidisciplinary doctoral programme network and to the long-term funding of researcher training. The SAFIR programmes play an important role in supporting researcher training in the field of nuclear safety. The collaboration of all organisations is essential, particularly with respect to the exchange of researchers across sectoral boundaries. The Doctoral Programme for Nuclear Engineering and Radiochemistry, active in 2012–2015, co-ordinated by Aalto University was a prime example of broad-scale collaboration partially funded by the power companies along with the Academy of Finland. The collaboration continues within the scope of the national Doctoral Education Network in Nuclear Science and Technology set up in 2016 through common events such as workshops and summer schools, but without funding for doctoral research.

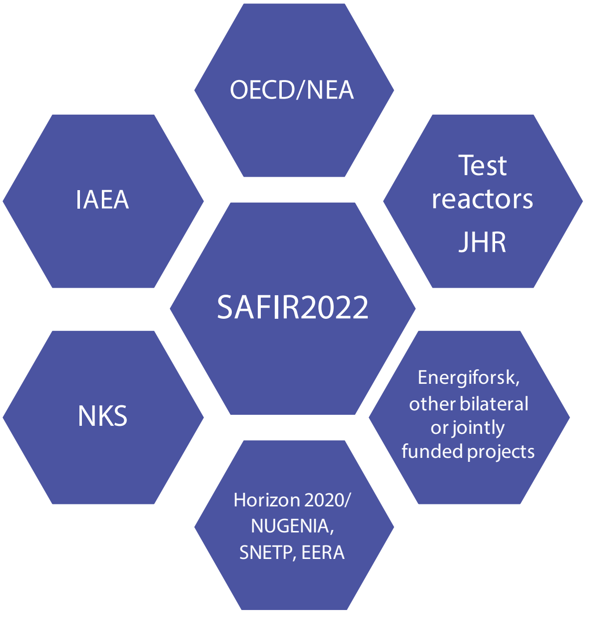
2.9 International co-operation

2.9.1 International co-operation as part of the research programme

International co-operation is a necessity in the nuclear power field, particularly but not limited to small nuclear power countries such as Finland. Co-operation enables access to larger research projects in Europe and elsewhere, thus ensuring a sustainable critical mass of necessary competence. In addition, co-operation is needed for performing large-scale experiments aimed at the validation of safety assessment analysis codes. International co-operation can also provide safety analysis software the use of which in Finland would otherwise remain limited or maintenance would not be possible [5].

The international co-operation included in the research programme must support the implementation of the goals of the research programme and benefit Finnish nuclear safety research as efficiently as possible. In the SAFIR2022 programme, international research collaboration emphasises OECD/NEA experimental and state-of-art-survey projects between member countries as well as participation in the Nordic NKS collaboration. In various committees of the OECD/NEA and IAEA, only actual research projects and equivalent development of nuclear safety assessment capability is funded by the SAFIR2022 programme. As an example, Finland's participation in OCED/NEA large-scale experiments, including safety assessment code validation activities and in the USR NRC CAMP and CSARP projects, has also been channelled through the research programme. Moreover, Finland has taken part and partly lead the survey projects concerning state-of-art solutions in seismic hazards and utility monitoring systems in order to better understand the assessment criteria between low, intermediate and high-level seismicity areas.

Figure 2.2 International co-operation in SAFIR2022 research programme.



Research cooperation within European and Scandinavian countries is considered beneficial due to the shared expectation of a high level of nuclear safety, strong safety culture and common environment for the use of nuclear energy. In nuclear safety, joint projects receiving funding from Finland and Sweden have been carried out in the SAFIR2018 programme. This co-operation is expected to increase in the coming programme period as the joint research with Energiforsk is expected to increase. This cooperation with Energiforsk started with research on polymer ageing and has been widened to include research on Barsebäck reactor pressure vessel materials. Measures have been taken to enhance co-operation between the SAFIR research programme and EURATOM nuclear safety research projects in Horizon 2020. The Memorandum of Understanding (MoU) was signed by NUGENIA and the MEAE in 2016 with the aim of further enhancing co-operation between the SAFIR2022 programme and European nuclear safety research.

Results from earlier programmes, a strong Framework Plan and an interesting research entity of the new programme with subsequent high-quality results will make the SAFIR2022 programme an internationally desired contract partner. The forms and practical implementation of international co-operation are discussed below from the perspective of the SAFIR2022 programme. However, it must be considered that international co-operation is bidirectional.

2.9.2 Forms of international co-operation in the programme

In the new programme, the established practice for the OECD/NEA experimental projects and NKS project along with Scandinavian jointly funded projects that have proven functional should be continued. Particular attention must be paid to the existing projects, which continue during the change over from one research programme period to the next. The continuation of the projects and ensuring the utilisation of the results of the projects is considered crucial. It is also important as part of the new programme to more effectively use the experimental projects for training new researchers and familiarising them with international networking, as well as developing their skills in communicating their research. The international co-operation and international experimental work at the Finnish new hot cell facilities at VTT CNS and the Nuclear Engineering Laboratory at LUT should be promoted.

In the new research programme, participation in the IAEA and OECD/NEA committee and workgroup activities is also important. This work can be included in the research programme within the available resources when the work directly serves the purpose of the research project or research project entity in question and produces clear research output that can be reported to the research programme. The same applies to summer schools arranged by the IAEA, OECD/NEA or ETSON for junior researchers.

The most challenging areas of the international collaboration of the SAFIR2022 programme are collaboration with the EU projects and the NUGENIA community's research projects based on agreements. With both of these, it should be ensured that the collaboration promotes the SAFIR2022 programme's goals in a measurable way. In addition, the collaboration should benefit Finnish nuclear safety research as much as possible, and should be capable of being implemented within VYR's funding terms.

Research focuses on second and third generation fission reactors (but the development of future technologies is considered as necessary) and therefore the NUGENIA Association is a natural partner for the SAFIR2022 programme. NUGENIA is a part of the European Sustainable Energy Technology Platform (SNETP).

The Finnish laboratory assets for nuclear safety research are enhanced not only in Finland but also abroad after the commissioning of The Jules Horowitz research reactor (JHR) in France. The JHR will be the key reactor in Europe concentrating on research into materials and nuclear fuels. The material tests are expected to be shifted from the Halden Research Reactor in Norway to the JHR. The new reactor is scheduled for completion by around 2022, and the first experimental programmes will start in 2024. Through VTT, Finland will have a 2% share of the reactor's research capacity and corresponding expenses. Planning for the utilisation of the JHR will most likely be commenced in the SAFIR2022 programme. Through the representation of VTT, Finland participates in all significant decision-making bodies and workgroups related to the planning of the use of the JHR. When the JHR is operational, the research in the OECD/NEA Halden research reactor will near the end of its useful life. Based on a comprehensive strategic review, IFE's board has concluded in June 2018 that the IFE will not apply for a new operating license after 2020 and that the Halden reactor will not be restarted. However, the nuclear research activities will continue in Halden. The reactor itself will turn to a decommissioning phase. Therefore, a major part of the fuel research in the current SAFIR2018 programme will move to the JHR.

The nuclear energy research strategy published by the MEAE in 2014 identifies existing, emerging and potential countries for bilateral collaboration where collaboration can take place either within the framework of a collaboration agreement between two existing organisations or through "Business Finland" activities between several Finnish organisations. In so far as such collaboration meets the goals set for national nuclear safety research programmes and has been approved by the executive bodies of the research programme, proceeding on a case-by-case basis is recommended. Where commercial aspects play a significant role, the natural place of the collaboration is outside of the research programme.

2.9.3 Practical implementation

The essential components in the practical implementation of collaboration are agreements, rights and obligations of the programme and international partners with respect to tasks and the ownership, use and publishing rights of the output.

For the OECD/NEA experimental projects, the present operating model – where the MEAE appoints the organisation representing Finland, the Management Board adds the project as part of a SAFIR2022 research project and appoints the representatives of the steering and programme groups – has proven functional. At the decision-making stage, attention should be paid to the internal Finnish communication within the programme and to the possibility of utilising the results of the experimental programme. It has been possible to pay the participation fee of the project directly from VYR funding, but the jointly funded part of the SAFIR research project has been applied for supervision of the project or safety analyses carried out.

Similarly, the present operating model does not need to be changed for the SAFIR2022 programme with respect to US NRC, NKS, Halden and Energiforsk projects. The JHR collaboration in connection with the SAFIR2022 programme requires a separate agreement model when the collaboration becomes current.

3 Research

3.1 SAFIR2022 operating environment – challenges and research needs

3.1.1 National operating environment

The planning period for national nuclear safety research for nuclear power plants until 2022 and beyond to 2026 involves regulatory review of construction licence applications and periodic safety reviews of nuclear power:

- The periodic safety review for Loviisa 1 and 2 NPP units: due 2023.
- Decision on renewal of the operating licence for the Olkiluoto 1 and 2 NPP units is under preparation at the time of writing this research Framework Plan.
- An operating licence decision is to be made for the Olkiluoto 3 plant unit.
- A construction licence decision is to be made for the Hanhikivi 1 plant unit.
- VTT FiR research reactor decommissioning licence.
- Terrafame uranium enrichment facility operating licence.

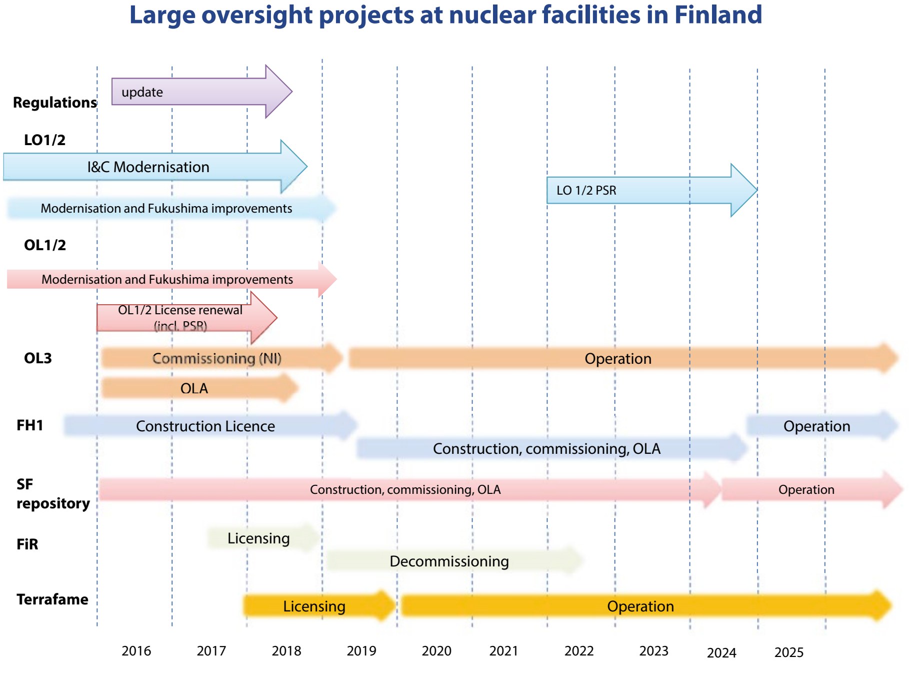
During the coming planning period, significant modernisation projects will be carried out at the existing Loviisa 1 and 2 and Olkiluoto 1 and 2 nuclear plant units, the largest of which, by volume, is automation renewal. Plant improvements and modifications planned particularly because of the Fukushima accident will most likely be continued during the programme period. While the Framework Plan has already been prepared, the MEAE has been handling the construction licence application for Hanhikivi 1. This application may also affect the related schedules and goal set for the new SAFIR2022 research programme.

The national operating environment for nuclear power is changing with the changing energy system. Flexible operation of nuclear power plants may be a reality in Finland in the future. The technology changes and digitalisation may be utilised to enhance safety. Also, new reactor concepts, such as Small Modular Reactors (SMR), might be an attractive solution in new energy systems, and so their safety features and concepts need to be understood. The general views on these areas are introduced briefly in the following, and more detailed research needs are identified in Sections 3.3–3.5.

Flexible operations

One factor affecting the national operating environment is the increased need for flexible operations, such as different modes of load following. Instead of researching flexible operation per se, it is proposed that the possible effects of flexible operations should be taken into account in the research in different areas, such as the behaviour of materials and structures, thermal hydraulic and reactor phenomena, the safety effects of external demands, the role of automation and the effect on control room operations.

Figure 3.1 Estimated schedule for licence applications and renewal projects of operating nuclear power plants and those under construction and design in Finland.



Technological changes and development

There are lots of changes ongoing continuously in the technology that provide possibilities for gathering and processing information more efficiently than by the current methods employed in the nuclear industry. These methods could make it possible to gain a better understanding of different issues, and the identification of these methods could be utilised to improve nuclear safety. Simultaneously, it should be understood how to implement them to avoid possible adverse effects.

One example of technology changes and development is a digital nuclear power plant, which is a future development direction for the multi-physics/multi-scale simulation technology. A digital NPP covers a wide range of technologies and corresponding research needs, and could be fruitful for novel research.

In the future, machine learning, big data, robotic process automation and artificial intelligence, for example, will be more and more prevalent. Such applications, utilised by other industries, should be considered for their potential to be applied in nuclear power. They have the potential to improve nuclear safety by cost-effective means.

More broadly, the emergence of digital networking and societal aspects, including social media and cloud services, are also changes to be taken into account.

Small modular reactors

The possible safety aspects of small modular reactors could create an entity large enough to justify research targeted at SMRs only. However, it is encouraged that SMRs will be considered as a part of research in different areas, similarly with flexible operations. The possible aspects for research regarding SMRs are, but not limited to, safety philosophy, physical barriers in novel solutions, emergency zone requirements, simulation and other computational methods, and new operating concepts.

3.1.2 Regulatory environment

The global nature of activities related to the use of nuclear energy and networking highlights the importance of national safety research. The principle of continuous improvement is applied to international safety requirements and safety guides. The most significant changes to the safety requirement levels were made after the Three Mile Island accident in 1978, the Chernobyl accident in 1986 and the Fukushima Daiichi accident in Japan in 2011. Both the international safety standards and the Finnish YVL Guides have been developed with mostly large (>300 MWe) light water reactors in mind, where the fuel is in the form of uranium dioxide with zirconium-based cladding and the safety philosophy mainly relies on so-called active safety systems (those that require external operating power). At the time of writing this SAFIR2022 Framework Plan, the international forums, such as IAEA and OECD/NEA, have started discussions on technology independent safety requirements, issues to be considered when licensing Small Modular Reactors (SMR) or passive front line safety systems and accident tolerant fuel materials.

The idea of limiting the impact of severe accidents on the environment has been integrated into the EU directive on nuclear safety, IAEA safety requirements and

WENRA recommendations as a goal for the design of a nuclear power plant after the Fukushima Daiichi accident in Japan in 2011. Therefore, early releases or large releases shall be practically eliminated. Other lessons learned from the Fukushima Daiichi accident integrated into the international requirements and recommendations deal with the independence of the regulatory body, transparency, leadership and management for safety, enhancement of defence in depth of nuclear power plants and safety improvements related to extreme external hazards. The development of the IAEA safety standards on SMRs or passive front line systems is not foreseen during the SAFIR2022 programme period.

In Finland, these requirements were considered during the total revision of the YVL Guides, which was completed in 2013, and the associated revision of the government decrees. In July 2015, STUK was authorised to issue binding regulations on technical details concerning nuclear safety principles. These regulations, repealing former government decrees (717/2013, 716/2013, 734/200, 736/2008), were adopted on 22 December 2015 and came into force on 1 January 2016:

- Regulation on the Safety of a Nuclear Power Plant (STUK Y/1/2016)
- Regulation on the Emergency Arrangements of a Nuclear Power Plant (STUK Y/2/2016)
- Regulation on Security in the Use of Nuclear Energy (STUK Y/3/2016)
- Regulation on the Safety of Disposal of Nuclear Waste (STUK Y/4/2016)
- Regulation on the Safety of Mining and Milling Operations Aimed at Producing Uranium or Thorium (STUK Y/5/2016).

The recent update of Nuclear Energy Act in 2017 considers the Nuclear Safety Directive Amendment (2014) and further enhances the Finnish nuclear safety framework.

The development of European nuclear safety standards has started according to the recommendations of the study completed in 2013 by the European organisation CEN/CENELEC. The preparation of the new standards is implemented as global collaboration; however, in some areas, such as the fields of construction technology and mechanics, standards based on the European premises may also be expected. Research preceding the standardisation related to the use of nuclear power is required for creating a solid foundation for the above work. For the research, the new regulatory environment further strengthens the need for consistent nuclear safety standards and procedures at the various operative levels internationally, while also incorporating new topics to nuclear safety research.

3.1.3 Development of expertise

Only high-level national expertise can ensure the safe use of nuclear power. At present, Finland has nuclear power plants in all stages of their life cycle and licensing processes. Expertise is needed for both the long-term use of nuclear power plants and also for new plant options. The necessity for high-level national expertise has arisen during the safety assessment of events at the plants, the modernisation of the existing plants and in the construction of new capacity. National expertise cannot be outsourced. The SAFIR2022 Nuclear Safety Assessment Capability Model (see Appendix 1) has been developed to facilitate transparent, measureable development of national expertise required by the Nuclear Energy Act, Section 53.

The use of nuclear energy is still undergoing a generation change while new actors are entering the field. This makes the maintenance and development of high-level expertise at the national level particularly challenging. The generation that commissioned nuclear power plants in the 1970s and 1980s has mostly retired. Nuclear safety research and modernisation projects of the operating nuclear power plant plants and the use of operating experience of the nuclear power plants provide an opportunity for experts from different generations to work together, facilitating knowledge transfer to the younger generation. This ensures that the available experience of constructing and operating nuclear power plants is exploited in the best possible manner.

A versatile and challenging operating environment has increased international interest in nuclear safety work and research carried out in this area in Finland. The diverse on-going projects of the licensees have increased the attractiveness of the companies in the field as employers, which is reflected in students' interest in the field, as well as in the number of applications for vacant positions. Finland also hosts international research projects. The operating environment provides diverse possibilities for the further development of international collaboration and for the internationalisation of researchers.

3.1.4 Experimental facilities

Nuclear research experimental facilities in Finland are top quality in comparison to the whole of Europe. The recently commissioned VTT Centre for Nuclear Safety, the LUT facilities for thermal hydraulic studies, the forthcoming Jules Horowitz Materials Testing Reactor in France, of which Finland owns a share, and many other laboratory facilities mean Finland is one of the few countries in Europe capable of investing in new experimental facilities. At the European level, hot cell facilities exist in many countries, but in most cases they are coming to their end of lifetime. The closing of the Osiris reactor in France and the technical and economic problems with the Halden reactor in Norway have turned eyes towards the JHR. VTT CNS in combination with the capacity of the JHR provide us with excellent tools for material testing and research. They also provide a proper environment for educating new experts. Taking into account the fact that all experimental facilities are and will be national investments instead of private investments, the commitment of the Finnish nuclear community is very strong in increasing our competitiveness in research.

During the SAFIR2022 programme period the VTT CNS operation will reach full scale. The investment aid from the Government for the CNS will be continued up to 2020, after which it is LUT’s turn to take on their share of the renewal of the experimental equipment. At the same time, the JHR construction project will be finalised and the operation phase with the first experimental programme planned.

LUT continues the development of experimental infrastructure by constructing a modern thermal hydraulic testing environment and in the meantime keeping the existing facilities operable until new facilities can replace the old ones. The main existing large facilities are PACTEL/PWR PACTEL and PPOOLEX, and the first step of the new development, MOTEL SMR, is currently under construction. There have been several separate effects facilities to address emerging issues in the past, and performing novel experiments on short notice is a special strength of LUT.

Starting from 2021, the development of the research environment at LUT will be accelerated to have several different configurations of MOTEL available. The LUT test facilities have been, are and will be used in international cooperation; projects with EU, OECD/NEA and power utilities.

LUT is an active member of the NUGENIA innovation community and uses the NUGENIA Open Innovation Platform to share project ideas and gather partners for international projects (funded by, e.g. EU H2020). LUT's experimental capabilities have also been needed in OECD/PKL projects, where PWR-PACTEL experiments are counterparts to PKL testing done by Areva in Germany. Furthermore, experimental capabilities developed under SAFIR programmes have also enabled or facilitated separate-effects testing with dedicated test sections for several domestic and international customers.

3.1.5 International operating environment and research topics

The international nuclear safety research protectives are diverse: After the Fukushima Daiichi accident in 2011 some countries have decided to phase out the use of nuclear energy. On the other hand, in some countries, there are large investments in capacity building and international jointly funded research facility development. The extension of operation of GEN II reactors, start-up of GEN III reactors and the development of immersing technologies such as SMRs and accident tolerant fuel are among the driving interests of nuclear safety research worldwide. Even though the perspectives of international nuclear safety research are varied, depending on the current status of national nuclear energy programmes, the decisions on the phasing out of nuclear energy in European countries have not yet affected joint nuclear safety research. This may be due to the fact that the policy of maintaining expertise in nuclear safety assessment through research activities may be seen as an option in the new situation—for example, in Germany. An opposite development in the UK has led to the strong enhancement of national nuclear research. However, the impact of Brexit on the UK's participation in European nuclear safety research projects is not yet known.

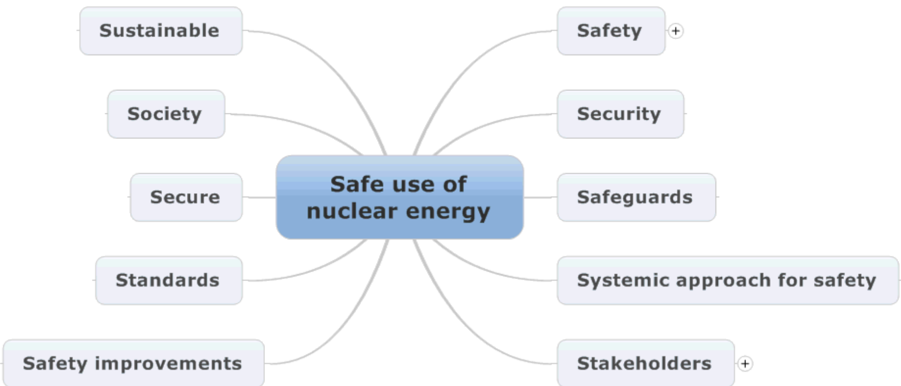
Fukushima Daiichi will be visible in many ways in the research topics of international organisations, particularly those of the OECD/NEA—from the analysis of the course of the accident to a variety of waste management and radiation protection issues. Research on the organisational, human and societal topics related to the Fukushima Daiichi accident has only started. It can be assumed that the topic will bring into research new questions on the actions of society and socio-technical communities. The systematic approach to safety is sought in different international forums. The management of supply chains for safety critical components is seen as a global challenge in the modern operating environment.

The OECD/NEA's experimental safety research projects have systematically studied phenomena related to fuel, the reactor, thermal hydraulics, containment integrity, the functioning of the containment structure and cooling capabilities of a melted core. The validation of safety assessment tools is one of the key aspects of the OECD/NEA projects. The accident tolerant fuels and reactor pressure vessel materials as well as the severe accident management strategies are expected to be activated during the SAFIR2022 research programme period. The OECD/NEA projects related to fire and hydrogen management will continue.

The research topics presented in the SAFIR2022 programme are strongly linked to European nuclear safety research and largely shared with the NUGENIA Roadmap 2013 and Euratom Nuclear Safety Research plans until 2020. The common topics in SAFIR2022 programme and the NKS-R programme – which is focused on thermal hydraulics, severe accidents, reactor physics, risk analysis and probabilistic methods, organisational issues and safety culture, decommissioning and plant life management including extension – establish the basis for nuclear safety research on nuclear power plants in operation in Scandinavian countries. Bilateral jointly funded projects are discussed above in chapter 2.

In addition, a continuation of the project concerning the Fukushima accident is underway and new information is gained on the severe accident behaviour of the reactor and the containment. Standards harmonisation work related to new facilities, carried out at the OECD/NEA, can be supported by research. Currently, the IAEA's ISSC (International Seismic Safety Centre) unit, established after the Fukushima Daiichi nuclear power plant accident, serves as the collector of global seismic research data. The ISSC is an important body as a communicator of information related to external threats. The fuel research at the IAEA is concentrated at FUMEX.

Figure 3.2 Safe use of nuclear energy.



3.2 SAFIR2022 Overarching topics and milestones 2022 and beyond

The SAFIR2022 planning group established eight overarching topics for which research goals were set until 2022 and for the next programme period until 2026. The need for multidisciplinary research and significance in achieving the programme goal characterise these chosen safety issues. The eight topical areas with the safety research goal are presented in Table 1. The goals are discussed in more detail in Chapter 3 and Appendix 1 "SAFIR2022 Nuclear Safety Assessment Capability Model".

Table 1. Overarching Safety Goals for SAFIR2022 programme and beyond.

Topic	Overarching Goal 2022	Overarching Goal 2026
1. Nuclear safety assessment capability building	Appendix 1 VTT CNS Hot Cells commissioned and facility in operation LUT Thermal hydraulics laboratory renewal completed Updating of impact test facility for current and future needs Enhanced PRA modelling capabilities and applications for new technologies	Appendix 1 VTT CNS Hot Cells on-going projects LUT Thermal hydraulics laboratory commissioned and projects running Experimental work close to full-scale scenarios Applications of enhanced PRA capabilities
2. Overall safety and systemic approach to safety	Approach for assessment of overall safety and systemic approach to safety developed Modern methodology in control room assessment, systems engineering in design, I&C and electrical systems assessment in use Insight for combining safety and security requirements achieved	Application of overall safety approach and systemic approach to safety assessments Continued methodology development with moderns tools and for complex working environment Insight for assessing combined safety and security issues achieved
3. Validated tools for reactor and nuclear power plant analysis	Availability of advanced analysis codes, flexible research facilities and accomplished safety experts able to address licensing questions and topical safety concerns. Analysis Codes and tools international benchmarking ongoing	Applications for the new set of analysis codes and tools ongoing, international publications for references, Commercial services for international customers.
4. Nuclear fuel and its lifecycle from reactor to final disposal	International experiments on fuel safety, experimental fuel research and use of test facilities and laboratories planned, international co-operation with JHR MTR planned Rethinking the fuel safety criteria Knowledge of accident tolerant fuel safety issues	Full utilisation of national and international test and laboratory assets in international projects
5. Ageing phenomena and integrity of barriers	Enhanced understanding for ageing management of materials, structures and components. Understanding of all types of Reactor Pressure Vessel materials and new materials for 60/80 years lifetime, Developed safety and structural integrity analysis methods contributing structural integrity of materials, structures and components. Non-destructive examination methods with high resolution for demanding components available, digitalisation.	Mastering aging management of materials, structures and components for safe and reliable LTO operation of nuclear power plants Continuation of up-to-date R&D to maintain structural integrity of materials, structures and components Enhanced reliability of non-destructive testing methods applied in structural integrity and safety of metal and concrete structures. Applications, commercial services, JHR MTR co-operation, bilateral co-operation

6. Severe accidents	Integration of Fukushima lessons learned into Finnish context Capability to assess all national severe accident approaches	Codes and tools for assessing passive severe accident management
7. External 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, air plane collision and explosions.	Continued methodology development and maintenance of hazard estimates
8. Nuclear safety in a changing environment	Understanding SMR safety concepts and the Finnish nuclear safety regulation Digitalisation as an opportunity for nuclear safety Understanding the impact of changes in the energy systems and crating new research topics.	Deepened understanding of SMR and safety requirements Digital nuclear power plant concept Development of necessary assessment methodologies. Defining NPPs safe operating modes with increasing distributed/renewal electricity supply,

The goals for 2026 are indicative and will serve as one input for the planning of the research programme period after SAFIR2022.

3.3 Overall safety and systemic approach to safety

3.3.1 Description of the research area

Overall safety and systemic approach to safety collects a wide range of nuclear safety research areas that are overarching between several topics, as well as topics affecting the nuclear power plant as a whole or that are present in several areas.

Such topics include the concept of overall safety itself, organisational issues, automation architecture, control room design and operations, human factors, external hazards, safety and security interfaces, electrical systems, setting the safety requirements, and controlling the plant design throughout the plant lifetime. All in all, practical implementation of a graded approach concept would benefit from a more holistic view of overall safety.

3.3.2 Objectives of the research

The main objectives of the research area in the SAFIR2022 programme are to:

- further develop a structured approach to balanced safety requirements,
- maintain and develop know-how on conventional and modern MCRs (main control room),
- maintain and improve modelling capabilities of PRA (probabilistic risk assessment),
- deepen understanding of HOF (human and organisational factors) and HFE (human factors engineering) aspects, and
- further develop the framework for evaluation of overall safety.

It is expected that by the end of 2022 we will have available:

- a methodology for evaluating the adequacy and balance of the requirements;
- an understanding of specific features and the safety concepts of SMRs and reflection to the current safety philosophy in Finnish nuclear regulation;
- the integrity of probabilistic and deterministic requirements to ensure adequate and fair application of defence-in-depth, including safety margins in the design;
- modern approaches to support and evaluate control room design;
- methods and tools to support a systems engineering approach in safety design;
- insight into how to optimally combine safety and security requirements; and
- sound design approaches of I&C and electrical architecture to ensure safety.

The identified goals of the research that go beyond 2022 are to achieve:

- a tool to evaluate the adequacy and balance of the requirements;
- an understanding of and more detailed modelling of the system of organisations in order to evaluate systemic behaviour of the complex network in different situations; and
- a deepened understanding of SMR safety features and the implications for safety requirements.

It should be noted that these are not the only goals beyond the period for SAFIR2022, but they do represent general top-level objectives that need support from many research topics from different areas in SAFIR2022 and in KYT2022 in order to be achieved. It is expected that these will be further developed during SAFIR2022 when preparing for the following period and combining the SAFIR and KYT programmes.

Out of the overarching research topics of SAFIR2022 presented in Section 2.5, overall safety is directly linked with topics 2) overall safety and systemic approach to safety and 8) nuclear safety in changing environment. Due to its systemic and holistic nature, overall safety also interacts with the other topics in the list.

3.3.3 Research needs

There are top level requirements for the use of nuclear energy in the Nuclear Energy Act (990/1987). The driving principle is that "the use of nuclear energy, taking into account its various effects, shall be in line with the overall good of society" (990/1987, Section 5). Furthermore, "the use of nuclear energy must be safe; it shall not cause injury to people, or damage to the environment or property" (990/1987, Section 6). The requirements concerning safety are further elaborated on in Chapter 2 A of the Nuclear Energy Act, where the guiding principles state that "the safety of nuclear energy use shall be maintained at as high a level as practically possible. For the further development of safety, measures shall be implemented that can be considered justified considering operating experience and safety research and advances in science and technology" and that "safety requirements and measures to ensure safety shall be sized and allocated to be commensurate to the risks related to the use of nuclear energy".

3.3.3.1 General safety approach and balanced safety requirements

It appears that although the general principles are rather well formed and they have been applied for a long time, one can question how these actually affect the more detailed safety requirements. Especially the overall good establishes societal expectations for the use of nuclear energy, which is not usually addressed when setting safety requirements. This also includes financial effects of safety requirements, a topic often omitted in safety research, but affecting the societal acceptability of nuclear energy through the top level expectations above, and further the selection of reasonably practicable solutions for safety features and improvements. From the point of view of society, the relation of expectations may well include the approach to the overall concept of safety, how safety in general is perceived, how risk is perceived, or how to proportion nuclear safety risks to other risks. The balance of safety requirements that is asked for by having requirements commensurate to the risks usually takes into account the direct consequences of the operation and possible accidents, but including other expectations that affect the concept of safety may not be such an easy task. Still, these expectations are underlying 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 justified level of safety requirements, these underlying expectations should be understood adequately.

Balanced safety requirements provide that a graded approach is utilised when structuring the regulatory framework for nuclear safety. Deterministic and probabilistic arguments are both valid, and usually deterministic requirements set the range of aspects that need to be taken into account in the design and operation of the plant, whereas probabilistic requirements, in rough, set the reliability level of the means to take care of the situations defined deterministically. There should be a methodology available to evaluate the adequacy and balance of the requirements.

These aspects are valid also in the KYT2022 programme, and especially the overall safety or risk perception and the acceptability of use of nuclear energy should consider a wider perspective than that covered directly in SAFIR2022 only.

3.3.3.2 Overall safety concept and systemic approach to safety

An overall safety evaluation tries to answer the needs above partially. However, the concept of overall safety is not well established. Therefore, understanding the different aspects and areas of safety needs to be further studied. 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 the more comprehensive approach, the contribution of different areas and their importance to overall safety can be identified, as well as the need to further enhance understanding of specific issues and identify gaps in knowledge. Furthermore, from the research programme point of view, it would be beneficial to 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 programmes. Safety analysis reports (SAR, FSAR) are intended to comprise an overall safety view of a nuclear power plant. Regarding nuclear waste, a safety case is a corresponding overall safety representation. ISO 15288 "Systems and software engineering – System life cycle processes", a non-nuclear standard widely adopted in safety significant industries, provides valuable background for overall safety. At least three dimensions of overall safety can be basically found considering a system of systems: technical architecture of a NPP, organisation of organisations and processes (systems engineering).

In order to promote the utilisation of the development in overall safety assessment frameworks, they should be tested in practice. A fruitful approach could be to apply them in SMRs that may have a different safety concept than those in 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.

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

3.3.3.3 Human and organisational factors

Human and organisational factors (HOF) affect all stages of safety related decision making; technology development and implementation, application of safety assessment methodologies and other daily activities at the utilities. Further work is needed to effectively integrate human and organisational factors knowledge to the nuclear context. It must be noted that this area is not isolated, but rather is part of other areas studied in the SAFIR programme, and therefore the interactions between different research topics should be identified and taken into account in the research.

Human and organisational factors expertise in the nuclear domain require solid knowledge of the state of the art research in a broad spectrum of behavioural and organisational studies, as well as knowledge of the national safety regulations, international requirements, best practices and industry needs. It is essential to look after, maintain and further develop expertise in HOF themes that have been studied in the previous SAFIR programmes, such as safety culture and control room behaviour and validation. Expertise is needed, for example, to understand and evaluate the underlying organisational and human factor aspects of individual and group behaviour.

Novel viewpoints are needed because recent international requirements [IAEA GSR Part 2] have put more emphasis on the importance of leadership for safety. Assessment and improvement methods for leadership behaviour and management decision making are needed. Different aspects should be incorporated into the safety culture framework, and potentially conflicting objectives within the organisation should be part of the overall evaluation. One important issue in the future is the changes in the operation environment, when an organisation is facing challenges to recruit and maintain expertise. This kind of situation may arise, for example, when a plant's lifetime approaches its end. Knowledge and tools to support sufficiency of staffing and the means to maintain motivation are needed. Furthermore, the safety culture of different organisations and the effects of the differences or commonalities in these on the overall safety need to be understood. Nuclear industry organisations carry out different initiatives for improving, for example, safety culture, human performance, usability, project management, organisational learning and leadership, but the understanding of the effectiveness of these initiatives may remain vague, and could be studied to support their effective mutual prioritisation, implementation and integration at all levels of defence in depth.

Currently, it is clear that a human factors engineering (HFE) programme should be developed when designing modifications for control rooms and I&C user interfaces. However, the scope of HFE should not be limited to control rooms alone. The potential safety contribution of HFE in other modifications to NPP systems, structures and components should be better understood. Also, principles for grading HFE activities should be developed.

Digitalisation may bring about different kinds of new technological solutions to NPPs that can be used for monitoring the condition of the system and structures, analysing data, decision making, etc. The human-technology interaction challenges and their safety relevance should be better understood.

The large proportion of abnormal events that take place in NPPs are related to human performance and human factors. Effectiveness and possible restraints to effectiveness of human performance development programmes should be understood better. The application of human performance tools in non-traditional areas, such as the prevention of human errors in design modifications, could be explored.

3.3.3.4 PRA

Balanced safety design is an important part of overall safety. An essential tool or methodology to evaluate this is probabilistic risk assessment (PRA), which gives core damage frequencies (CDF), large release frequencies (LRF), as well as large early release frequencies (LERF) as outcomes. Furthermore, contributions from different events to these are included. The results in general can be reduced to frequencies above that and 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. PRA methodology could also be extended, with some precautions, to evaluate the balance of the regulatory safety requirements.

There are issues that need better analysis and modelling approaches in PRA studies. In many cases, however, PRA modelling power is sufficient, but the applicable data and reliability models are inadequate. Examples are digital I&C, hybrid or digital control rooms, human reliability aspects, maintenance errors, reliability of passive systems, long mission times, security aspects, and ageing aspects. These issues, however, cannot be just introduced to PRA models on the basis of current understanding. Rather, from the PRA point of view, it should be formulated what kind of information is needed, and the understanding of the issue itself should be increased by specific research to answer this demand. PRA methods should also be extended to better include assessment of the whole site, which could be especially important when assessing SMRs with several reactor units at a single site and units sharing common safety systems and staff.

Co-operation between deterministic design and PRA should be studied. Deterministic design and PRA benefit from each other especially when there is good information exchange in practice. Design areas such as seismic design and fire protection design should be supported in research in order to enforce the co-operation with corresponding PRA. Seismic design margins are assessed with extreme external hazard requirements (DEC-C) and it is important to review the methodology compared to different countries, such as in France. Defence in depth design of fire protection is assessed with PRA in order to ensure the functionality of safety systems and mitigation of fire spread against different kinds of fires. Methodology compared to different countries, such as the US, should be studied.

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 link between probabilistic consequence assessment (PRA level 3). To support this the modelling capabilities for PRA level 3 need to be developed further, which includes linking both PRA level 2 studies and environmental consequence analyses in a proper manner. Furthermore, the model development and research on this topic could provide insights to the overall safety of operating NPPs and those under construction and design.

3.3.3.5 Systems engineering

Tools to support design processes may help to ensure that safety requirements are adequately taken into account in the design and during design changes, help in configuration management as well as in taking into account inter-disciplinary effects. In general, these tools may help to treat the NPP as a whole. Although these tools may be mostly utilised by the licensees or the vendors, their development may enhance nuclear safety through more reliable requirement management, ensuring the integrity of the design, and the more fluent implementation of safety improvements. Model checking tools help in finding possible design errors, and they need to be further developed to support failure mode effect analyses.

There are some safety requirements that might be mutually somewhat contradictory. Typical examples are requirements regarding the reliability of safety functions, avoiding inadvertent actions, and security issues, for which independent requirements exist but they are not necessarily coordinated as an entity. From this point, it should be better understood how functional and non-functional requirements should be combined to optimise the overall system efficiency instead of partial optimisation. Here, architecture, the system and component level should be considered by taking a systems engineering approach. A related issue worth considering is the overall safety level reached with qualified redundant systems compared with that of non-qualified but diverse systems, the latter potentially allowing for an even better safety level utilising industry level components, and leading to less complicated and more robust design.

3.3.3.6 Safety and security interface

Security is one specific area within overall safety, but it is not fully isolated; there are interfaces with safety issues and it is important to identify what the sources of conflicting requirements are, and where requirements aim at the same outcome. It may be difficult to include research on specific security threats in the SAFIR2022 programme, but a general approach may be studied from the point of view of how safety and security requirements are related and connected to each other, and what would be the optimal way of responding to the objectives above when developing the requirements. In particular, both safety and security issues should be considered systematically, such as utilising the systems engineering approach (see previous item on systems engineering), solving interfaces and possibly contradictory issues.

3.3.3.7 I&C systems and electrical systems

Instrumentation and control (I&C) systems and electrical systems affect the majority of functions of an NPP. Therefore, careful I&C architecture design and implementation is essential, and the tools to support a sound design are needed to ensure the reliability of the safety functions in different situations. Essential interfaces with the I&C design and control room operations have to be identified and included in the research in order to direct the research effort properly. Hybrid control rooms will be more common in the future, and the different aspects related to these need to be studied. Electrical systems support a variety of safety functions, and therefore knowledge of the effects of different disturbances – resulting from both external and internal sources of the plant – are important to understand, which seeks better protection of the plant from these kinds of faults.

3.3.3.8 SMRs

Although the main emphasis of the SAFIR2022 research is to support current LWRs in different phases of their life cycle, SMRs are also an attractive entity for overall safety research since there is relatively little historical burden (legislation, requirements, practices, conventions, culture) limiting novel approaches, if applicable. Such approaches could be applied, at least partially, to challenge the overall safety view of existing light water reactors, and give new insights into the topic. SMRs are selected as a specific general technological area to approach different topics.

The rationale supporting SMRs often given is that they are safer than the current technology. Therefore, more information is needed to support this somewhat vague statement. The potential for early releases and large radioactive releases from SMRs should be evaluated. In addition, applying more passive systems to ensure safety functions and the concept of defence in depth could be the subjects of research.

To support maintaining knowledge on nuclear-specific work psychology, some basic research could be directed to specific aspects that may come up with SMRs. These new questions – for example, in control room operations – include the remote operation of an NPP and controlling several units from a single main control room.

Furthermore, although not related to SMR operations only, adaptive power production due to load-following demands may arise in the future, and this would require decision making, the flow of information and control room operations that are different from the full load operation that is the usual type of power operation currently in Finland. It should be identified what kinds of safety aspects could arise from these demands on control room operators, possibly affecting the optimal training and design of operations.

Figure 3.3 Loviisa plant (source: Fortum).

3.4 Reactor safety

3.4.1 Description of the research area

Reactor safety research focuses on the development of experimental and computational research and analysis methods aimed at ensuring that a nuclear facility and its systems are able to implement the safety requirements set for them. The research questions in the area of reactor safety 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, including phenomena relevant to accident progression and resulting consequences. A basic requirement for all the activities related to reactor safety is the availability of sufficient expertise, analysis tools and research facilities required to handle the issues relevant today and in the future.

3.4.2 Objectives of the research

The main objectives of the research area in the SAFIR2022 programme are:

- To develop and maintain a comprehensive understanding of matters relevant for reactor safety. This includes understanding of the phenomena, analysis tools and methods, related uncertainties and nuclear technology covering both the present technologies in use in Finland and those foreseen in the future.
- To provide sophisticated and validated tools and methods for safety assessments and licensing of both new units and modifications of existing units. The available tools and methods must form an entity with which authorities can independently assess the acceptability of the submitted plans and applications.
- 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 concerns relevant for the whole life cycle of nuclear fuel and facilities, including also fuel transports, interim storage and final disposal.

It is expected that by the end of 2022 we will have available:

- a new validated set of analysis codes and tools that are ready for the applications to follow,
- research facilities with an active role in nuclear safety work and with the flexibility to adapt to future research challenges,
- both new and experienced safety experts able to solve computational and experimental research questions, and
- a better understanding of nuclear safety.

All work in the field of reactor safety should also consider possibilities for international collaborations with the aim of taking advantage of the best available knowledge, the spread of information, focusing the national development and research needs to relevant areas, training new experts and increasing the utilisation of national research tools and facilities. One of the means to increase visibility at the international level is to publish as many high-quality scientific journal articles and conference papers as possible within the SAFIR2022 programme.

3.4.3 Research needs

3.4.3.1 General method development

A better understanding of nuclear safety as a whole requires a better understanding of the fundamental phenomena, processes and events. Here the roles of both computational and experimental research methods are emphasised and the best progress can be achieved when the studies performed support and complement each other.

The analysis of complex multi-scale, multi-physics phenomena requires sophisticated computational tools and methods, covering core neutronics, thermal hydraulics and fuel behaviour. The calculations involve specialised codes and a combination of different computational models. Applying high-fidelity methods, such as Monte Carlo neutron transport simulation and CFD (Computational Fluid Dynamics) for thermal hydraulics, leads to higher accuracy, but it also dramatically increases computational cost. It is therefore important that traditional reduced-order methods are developed and maintained as well. The methodology applied to multi-physics calculations cannot be limited to individual codes, but should cover the complete calculation system, including coupling algorithms and interfaces between different physics solvers. The use of existing codes and tools versus the development of new codes and tools needs to be based on careful consideration aimed at the optimal allocation of available resources. An example of a novel approach to core physics is the Kraken computational framework, which is largely based on the Serpent Monte Carlo code, and developed in SAFIR2018.

Reactor safety analyses deal typically with very complex phenomena and are based on limited and uncertain knowledge. Therefore, proper understanding and management of the related uncertainties is necessary for the validity and usability of the results. The traditional use of conservative assumptions can be justified in many cases, but the use of more realistic best estimate methods supplemented with uncertainty analyses can be better suited for certain applications and help in the proper allocation of design requirements and technical solutions. A better understanding of the relevant uncertainties and their sources and effects is needed to improve the usability of the analysis results, to support the development of best estimate methods and to facilitate the selection of suitable analysis methods. The analysis of passive safety systems and features is one example where the proper understanding and propagation of uncertainties may be critical for the analysis outcome.

Probabilistic analysis methods are already widely used in many kinds of applications, but due to their ability to handle complex dependencies, to demonstrate the relative importance of items and to facilitate the management of uncertainties, even new application targets should be considered. Also, the present analysis methods and tools should be advanced further to increase the accuracy and speed of the analyses as well as to improve the elucidation and usability of the results. Possible ways of improving such aspects include further development of calculation algorithms, more versatile modelling of timing-related parameters and dependencies, including initiating event frequencies, component failure probabilities and the use of success criteria in event trees, and the further development of the use of importance measures.

3.4.3.2 Validation of the tools

Proper validation cases are needed to support the development of the computational codes. The development of the validation cases should consider the use of both national and international research infrastructure. One important related activity is the development of experimental measuring technologies, which are needed for the acquisition of accurate and extensive measurement data.

Validation activities should also consider the possibilities of extending the usability of current software tools to new application areas such as the transport and storage of nuclear fuel. Special cases where more work is needed include passive safety features, small modular reactors (SMR) and accident tolerant fuel. The possibilities for better use of the vast amounts of data collected at the plants could also be studied further.

3.4.3.3 Severe accidents

Analysis of severe accident phenomena as well as plant systems and strategies intended for severe accident management is a research area where the upkeep of sufficient national competence is necessary. Participation in international research projects concentrating on the Fukushima Daiichi accident is considered to be very important. For example, the mechanisms related to the containment failures at Fukushima Daiichi need to be understood.

Research questions related to the timing, characterisation and spread of radioactive releases also possess a high safety relevance. The utilisation of passive safety features for severe accident management is important especially for new plant designs and should be studied using both computational and experimental research methods. Due to the considerable uncertainties associated with severe accident phenomena, the better combination of deterministic and probabilistic analysis tools is vital for the improved understanding of the risks related to nuclear operations.

3.4.3.4 Hazards

Past experiences have shown that external hazards, including seismic events, may be very important contributors to nuclear safety. Therefore, even though a lot of research has already been carried out in this field, further research is necessary to maintain and improve the knowledge related to critical phenomena and their consequences. 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.

Information on external hazards is required for determining the design basis of new units and in the reassessment of the design basis in connection with periodic safety reviews. The same information on external hazards is typically required for the determination of the design basis and for the implementation of probabilistic risk assessments.

The licensees are responsible for analysing the external hazards at nuclear power plant sites. In practice, the licensees often use national expert organisations as consultants in the analysis of external hazards. The work in the previous 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.

Earthquakes have to be taken into consideration in the design of nuclear facilities but in Finland there are no seismic requirements for conventional buildings or installations. Therefore, there is hardly any research on the seismic hazard in Finland for other purposes. The seismic hazard is regional in character and it is important to create and maintain sufficient national expertise in the field. Well-known foreign consultants have an important role in supporting seismic safety in Finland but national efforts are required for collecting and analysing national basic data. Therefore, the role of the SAFIR programme is especially important regarding seismic hazard and seismic safety in general.

Seismic hazard research requires a consensus on estimating attenuation effects between the source and utility as well as monitoring needs at utilities and other measurements in Finland. This has been studied lately in OECD/NEA and these results should be available for further research. Moreover, the latest measurements should be studied further from the viewpoint of common design, DEC and PRA. Another issue is to find consensus also on other important parameters, such as maximum magnitude assumptions in low seismicity inner areas of continental slabs. One possible topic for further research is the structural mechanics modelling of displacements, which could give new insights into the near field effects, which are difficult to assess on the basis of observational data only.

Meteorological and hydrological research is conducted extensively also for other applications, including building regulations, land use planning and infrastructure protection. However, for nuclear safety, much less frequent phenomena and intensities are of more interest than in most other contexts. The results of general meteorological and hydrological research are typically not sufficient for nuclear safety purposes. The SAFIR projects also provide a good forum for cooperation with other research projects in the field.

Since many external hazards are regional, the national expert organisations (e.g. Finnish Meteorological Institute, Helsinki University Institute of Seismology) have an important role in collecting and analysing the measurement data. In addition to the statistical treatment of measured time series, the physical modelling of hazards should be used to assess events with very low frequencies. The SAFIR programme should also be used as a forum to bring together experts from different organisations and in creating a national understanding of the external hazards in Finland.

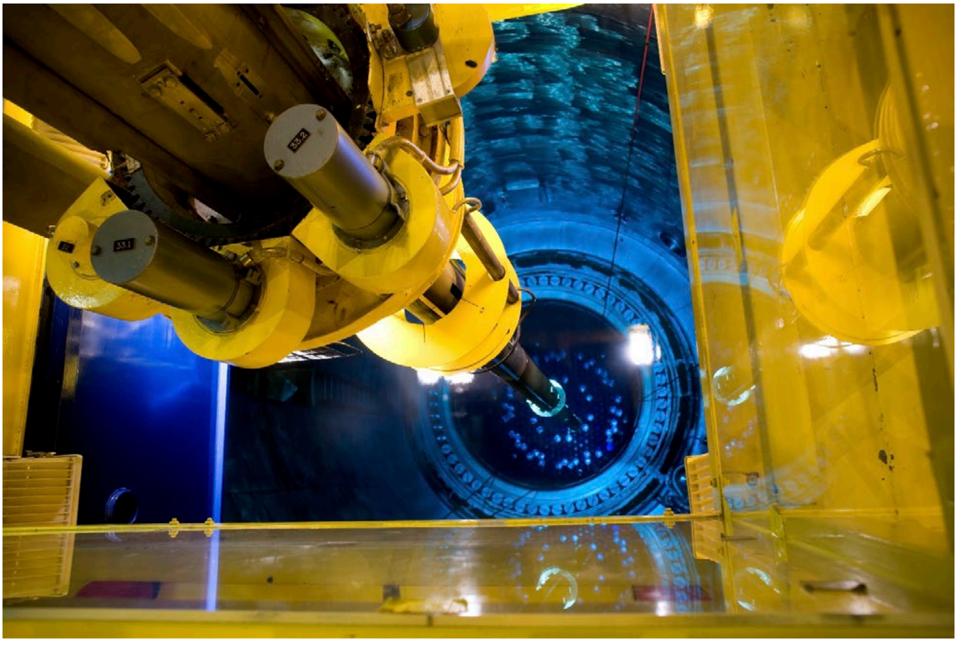
In addition to external hazards, internal hazards also have to be taken into account in the design of nuclear facilities. The greatest research interest in this area falls upon fires that may cause complex consequences for the engineered safety features, such as simultaneous initiating events and system unavailability, including system failures and spurious actuations. Best estimate methods for the modelling of fire spreading and fire consequences are needed for the improved understanding of the risks related to fires and for the design of properly dimensioned plant features where such risks are minimised.

Due to the wide spectrum of possible hazards and their effects, the application of probabilistic analysis methods is needed to support the safety assessment of existing and new NPP units and in the design of new safety features to make sure that different hazards are taken properly into account in the design specifications and that the resulting risk profile is well balanced.

3.4.3.5 Fuel research

Research topics relevant for future activities include the use of burn-up credit in criticality analysis, phenomena related to burnup uprates, the properties of accident tolerant fuels and the possible introduction of new burnable absorbators. A review of current accident acceptance criteria for fuel, especially Reactivity-Initiated-Accident (RIA) criteria, would also be worthwhile taking into account the ongoing international activities such as OECD/NEA update of RIA state-of-the-art report and new experiments (e.g. CABRI). The research questions related to spent fuel behaviour during storage and transportation also provide a link to the KYT2022 research activities.

Figure 3.4 Replacement of fuel at the Loviisa plant (source: Fortum).



3.4.3.6 Electric systems

Plant safety and operational systems are typically dependent on electrical power. Past experiences have shown that electrical disturbances, such as voltage and frequency variations, originating both from the external grid and from specific internal plant components such as the main generator, may cause complex effects on different plant components. The improved ability to understand and model the origin, propagation and effects of such disturbances can help to strengthen the protections and ensure the proper coordination and application of plant-level versus component-level protections.

3.5 Structural safety and materials

3.5.1 Description of the research area

A prerequisite for the safe use of nuclear power plants is ensuring the durability of the structures, components and equipment and the reliability of the materials under all conditions related to the use of the plants. With respect to new plants and renewals related to materials, one must also be familiar with the key issues related to the manufacturability, manufacturing and repair technologies and inspectability of the components. These factors have already been addressed in earlier research programmes concentrating on nuclear safety, with which in-depth expertise has been acquired. Research programmes providing continuity have helped ensure the safety of our nuclear power plants that have worked reliably since the 1970s. In the new SAFIR2022 programme, there is a need to further increase the expertise in this area, producing the additional information necessary for improving the life cycle management of the plants and their materials taking into a consideration also the new processes for, for example, component manufacturing (additive manufacturing). A joint goal in all research is to ensure the reliability of ageing management throughout the plant's life cycle. In addition, new collaboration models and, in particular, development of international collaboration is needed.

The research area involves the ageing of the units. It will become a key area when modernising the operating nuclear power plants and building new ones. The area is also very broad, and therefore 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 where the aim is to benefit from expert collaboration. The goal is also to 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 operating life of the present plants has been or is being extended at least by 20 years from the original planned lifetime. The planned operating life of new plants under construction and in design is 60 years. With respect to the use of new plants, a significant goal is to implement life cycle management programmes so that life cycle management programmes are already complete before the plants are commissioned. Based on experiences from the plants currently operating, this has been deemed important, as ageing phenomena and the possibilities for managing them must be identified already during the design stage. Such factors include material selection, manufacturing and repair technologies, determination of loadings and the inspectability of structures and components at stages appropriate for the overall plant safety. Furthermore, the preconditions and assumptions made in the design of ageing management programmes should be understood and revised as necessary.

Operating stage factors such as the way the plant is run and plant transients play an important role in the long-term durability of the structures and components. Material and structural behaviour depends on load-follow loading. In-operation, monitoring information can be collected from the feedback obtained in the ageing management programme and through condition monitoring and inspections. Entities of their own in life cycle management are formed by plant modification and modernisations, which have systematically been implemented in Finland in order to ensure the operation and operating conditions of the plant compliant with modern requirements. In modernisation projects, ageing management procedures and the plant's operating and ageing information in addition to the design principles must be taken into consideration in the component and structure design stage.

Materials and components received from the decommissioned Swedish Barsebäck and Slovak Bohunice plants or from the existing Finnish or Swedish plants support ageing management and the related development. Plants that are decommissioned (pressure test and monitoring of the containment building to be dismantled in the Swedish Barsebäck plant) and decommissioned plant parts (steam generator replacements, pipeline renewals, reactor pressure vessel trepans, damage inspection) and research collaboration can yield valuable information on ageing phenomena. Knowledge regarding the procurement requirements and the operating durability of the original plant components provides important initial data for the renewed design.

In this respect, the most significant development project of VTT's research capacities, VTT Centre for Nuclear Safety, will create new possibilities for research.

Other structural safety and materials items are non-destructive examination methods, structural safety analysis and new material solutions.

3.5.2 Objectives of the research

The research must target the material and structural solutions of the operating plants and those under construction, the corresponding design and load data and the utilisation of research capacity and know-how acquired thus far. The research develops the basis for the assessment of the overall safety of the plants during all stages of the life cycle.

The aim of the research is to increase knowledge that supports the long-term and reliable use of our 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. At the same time, attention must be paid to the utilisation of structure and equipment-specific ageing information, considering the design and manufacturing related to the replacement of out-of-date plant components. The operative capability of the equipment and structures in exceptional conditions must also be taken into account.

The research topics are ageing (metallic, concrete, polymer, water chemistry, automation systems), non-destructive testing (NDT, metallic and concrete), structural safety analysis, preparation for new technologies, new material solutions.

Last years' Energiforsk research programmes have become important – for example, the common polymer programme. Research on reactor pressure vessel materials will be important in the SAFIR2022 programme.

In addition to metallic materials, polymer-based materials are used in a wide range of applications inside nuclear power plant containments, such as cables, sealants, paint coatings, lubricants and greases. An ongoing research project in the SAFIR2018 programme was established to provide better understanding of different polymer ageing, qualification and ageing management issues. The project concentrated on condition monitoring techniques, mapping suitable components for ageing studies and studying ageing mechanisms and effects inside the NPP containments, both experimentally and by using computational methods.

It is expected that by the end of 2022 we will have:

- better knowledge that supports the long-term, safe and reliable use of nuclear power plants,
- non-destructive examination methods that support the safe and reliable use of nuclear power plants, and
- better safety analysis methods that support the safe and reliable use of nuclear power plants.

3.5.3 Research needs

The needs of the research programme have been divided into four topics, the broadest of which is ageing, which includes the knowledge and modelling of ageing and the failure mechanisms of components and structures in nuclear power plants (both physical and chemical), including assessment methods for the radiation tolerance of materials and the effect of radiation on long-term characteristics. Life cycle management methods and life cycle extension belong to ageing research.

Non-destructive examination and assessment methods represent a research area where method development is continued for the assessment of the ageing of equipment and structures.

A central research topic is the advanced assessment methods of structural safety. In addition, in experimental and computational method development, overall safety must be considered in addition to the safety of components and structures. PRA-based and deterministic design: development of the connection between deterministic design and PRA and the development of assessment methods at the interface of the methods, including the development of planning methods for risk-informed in-service inspection programmes.

In addition, the goal of the programme is to implement projects that concentrate on new materials, the components and structures of new plants, and the material requirements and manufacturing and construction technologies of plant parts to be replaced or installed in the new plants.

The goal of the broad topic entity is to produce research results through experimental work and computational and modelling work. Therefore, it is feasible to implement the research in various project types or by combining them. These include benchmark studies, phenomenon-based experimental research and modelling, the development and implementation of new research methods and research on representative experimental structures and real structures.

3.5.3.1 Ageing phenomena and degradation mechanisms

Ageing management, design, construction, maintenance, long-term operation (LTO) and microstructure-related safety research is included in this chapter. The design, construction, operation, condition monitoring and maintenance of a nuclear power plant shall provide for the ageing of systems, structures and components (SSCs) important to safety in order to ensure that they meet the design-basis requirements with the necessary safety margins throughout the service life of the facility. The research needs focus on metallic, concrete and polymer materials, water chemistry and automation systems.

Understanding the environmental effect and load in the framework of the behaviour and characteristics of material is a key aspect of nuclear power plant safety. The topic covers the change of the characteristics of ageing plant materials during the life cycle, the determination of the changed characteristics (mechanical properties, etc.), the research into plant materials and knowledge of different operating environments and loads.

Current topics involving the failure assessment of the components of nuclear power plants include reactor vessel steels whose operating life is extended and stainless steels as pipeline materials, including their welds and dissimilar metal joints. Environmental assisted damage has been studied in national nuclear safety programmes for a long time now. Still, cracking phenomena are not properly understood or explained and therefore this topic needs to be continued also in the forthcoming programme. Understanding the role of the environment together with the residual and operational stresses and strains in nucleation and the growth of cracks are mostly important in predicting the life cycle of components and enabling their safe use.

Ageing also affects the mechanical and chemical behaviour of many organic materials. For example, the fire risk of cables may change during the operating life of a plant. Ageing may also occur in structural fire safety components, such as fire stops, but the phenomena and their importance are not sufficiently well known at present.

It is worth continuing the research and modelling of fracture mechanisms in order to ensure the durability of ageing plants and structural integrity, using more detailed and versatile computational analyses.

During the programme, it is important to develop experimental and modelling capacity suitable for the analyses of the durability and the structural integrity of new plants. The scientific goals are the research of cracks of real shapes and the applicability of the results to real structures.

In the assessment of radiation impact on materials, the central materials researched are reactor pressure vessel steels, reactor pressure vessel internals of stainless steel, high nickel and nickel-based alloys and fuel claddings. The goal is to determine the fracture-mechanical, creep and micro-structural characteristics while increasing the mechanistic understanding. With respect to reactor pressure vessel steel, conventional steels should be addressed along with the new type of Russian steel, and the impact of new and old manufacturing methods on the usability of the materials should be studied. New research needs and challenges are also present in the field of radiation tolerance of non-metallic materials, such as concrete structures and cable materials. In this field, it would be useful to carry out international collaboration for increasing new information and expertise.

Fuel cladding materials are a group of materials on their own whose research cannot be detached from fuel research. The cladding materials and fuels have developed significantly owing to the suppliers' work and use experience. This has also enabled the increase of burn-up limits implemented in Finland in recent years for the current power plants. A current research topic is the experimental research into cladding material behaviour in research reactor conditions.

An important research challenge in the field is the cumulative effect of ageing phenomena. In real plant environments, failures are rarely the consequence of a single phenomenon. Fatigue assessment may require observation of both mechanical and acoustic vibrations. The cumulative effect of different failure mechanisms, such as creep and fatigue, or corrosion and fatigue, cannot be assessed through individual failure mechanisms; their synergistic interactions must be determined as well.

International databases shall be used where possible to identify detailed research needs in Finland. Microstructure research will concentrate on more specific items, the balance between research and practical items shall be achieved.

Metallic

The ageing of metallic structures occurs when chemical, thermal or mechanical loading or neutron radiation causes changes in structure properties resulting in changes in most loaded areas, typically in welds where residual stress causes high-level preloading. A systematic approach in ageing management may lead to a large number of ageing mechanisms. The problem is that the real mechanical, thermal and chemical loading as well as transients of the structure are not known. In any case of ageing-based failure, there is one or more triggering mechanism. Representative usage of data as close as possible to the actual environment is the only fact that has use in finding the right mechanism and risk components to investigate.

Generally, the goal is to create experimental research methods for phenomena recognised as special questions in Finland, gathering new experimental data and developing engineering methods for managing phenomena leading to failure. Structural safety is largely based on understanding ageing phenomena and structural integrity. Unforeseeable research needs can be expected to emerge during the construction of the new units. Relicensing of existing plants and the extension of their lifetimes from the original licences for operation will focus the research on ageing phenomena during the long-term operation of the plant, As the estimated lifetime of new plants is 60 years and the decision and construction licence applications are made for additional capacity, the research needs of new plants will be an important part of the research area.

Structural integrity is based on recognising degradation mechanisms, finding the possible failures and determining their size, and assessing the rate of crack growth and propagation. It is essential to understand the failure susceptibility of different structural materials and components, as well as the impact of manufacturing techniques on failure sensitivity. In addition, the environmental conditions and structural loads have to be known. Research projects on metallic materials may include the embrittlement of reactor pressure vessel materials, the embrittlement of austenitic stainless steels of reactor internals, the structural integrity of pressure bearing components other than the reactor pressure vessel, the structural integrity of dissimilar metal welds, etc. Important degradation phenomena to be studied in addition to embrittlement are stress corrosion cracking, SCC (stainless steels and nickel-based materials), fatigue, including environmentally assisted fatigue, oxidation and other corrosion phenomena. The risk induced by a degraded system is taken into account by the PRA-analysis. The ageing assessment is then done by either a deterministic or partly or fully probabilistic risk matrix. Furthermore, the possibilities of preventing or mitigating degradation are handled in sections such as mitigation, inspection and monitoring.

Concrete

With respect to the load bearing function of the inner containment concrete wall and the leak tightness function of the liner, the leading ageing mechanisms are creep and shrinkage of the concrete in connection with the relaxation of the pre-stressing steel.

The creep and shrinkage of the concrete together with the relaxation of the pre-stressing steel lead to a decrease of the pre-stressing force and a decrease of the concrete compression stress. If this time-dependent process would last for an unlimited time, it would finally cause tensile stresses and cracks in the concrete under certain design load conditions.

Other important ageing mechanisms include steel and concrete steel reinforcement corrosion and chemical attack against concrete structures (concrete, reinforcement, steel liners, etc.). It has also been observed that corrosion and serious cracking have also been caused by formwork clamps made of aluminium and left in the structure. Corrosion attack due to sea water on steel reinforcements is possible in various parts of the cooling water structures and other reinforced concrete structures exposed to sea water, if cathodic protection has not been installed.

Concrete degradation becomes one of the main issues for the long-term operation of an NPP. Concrete degradation mechanisms (e.g. alkali-silica reaction, delayed ettringite formation, sulphate attack, reinforcement steel corrosion, freeze/thaw cycles, irradiated concrete, among others) have been detected in concrete nuclear facilities and have been linked to the loss of performance and the residual lifetime.

In this regard, one of the biggest challenges in dealing with ageing/deteriorating concrete structures is identifying the cause of possible distress, to establish the correlation between the modification in the mechanical/physical properties and the chemical reaction behind, to define the structural ultimate limit state (physical integrity) and serviceability limit state (structural performance and durability), to evaluate possible implications of the degradation and also their potential for further deterioration.

Special attention should be given to deleterious expansive reactions, which include alkali silica reactions (ASR) and delayed ettringite formation (DEF). ASR and DEF have recently become a top R&D priority for US NRC, CNRC, IRSN, EdF and FANC. Several international technical groups (RILEM and FIB) have begun to address these issues.

The casting of a massive safety classified concrete structure is a challenge. Hydration of cement induces high temperatures and temperature differences between the core and surface of the structures. The temperature can be measured during casting and drying, but simulation beforehand should be possible. Concrete structures have many kinds of requirements, such as the water tightness of the pools, but often there is a lack of acceptance criteria.

The ageing of concrete structures depends on the conditions to which the structure is exposed. The conditions can be monitored and structures inspected. Also, PRA analysis is a tool for determining partly or fully the probabilistic risk matrix. Research would be needed when actions have to be taken for various NPP reinforced concrete structures suffering from steel reinforcement corrosion and how renovations should be carried out.

Polymer

When it comes to ageing, the most critical applications of polymer materials in electrical and instrumentation/control (I&C) components are usually electrical insulation and sealant structures. Therefor the ageing of polymer materials is an important aspect for the safe and reliable operation of electrical and I&C components. The normal way of taking the effects of polymer ageing into account in the qualification of electrical and I&C components is type testing including artificial ageing treatments representing the ageing stressors of the intended design environment. Temperature and radiation are normally considered the most significant environmental factors causing the ageing of electrical and I&C equipment in the nuclear power plant environment, but depending on the application and the type of equipment, humidity, vibration and voltage can also have an effect on the ageing of polymer materials. In addition, the ageing atmosphere (e.g. nitrogen in some BWR containments) affects the ageing mechanisms, and exposure to several environmental stressors simultaneously can have significant effect on the resulting ageing degradation of polymer materials. High temperature has been identified as the most common stressor causing ageing, but also the effects of the other stressors need to be covered by the artificial ageing treatments in the type testing phase of the qualification. When arranging the ageing treatments, a typical practical problem is taking into account the combined effect of several stressors, because, for example, simultaneous irradiation and thermal ageing is usually difficult to arrange. Another aspect regarding arranging artificial ageing treatments is acceleration factors (e.g. thermal ageing time compared to the lifetime for which the equipment is being qualified for or the irradiation dose rate compared to the dose rates during normal operation or accident conditions).

The combined effects of the different ageing stressors and the effects of acceleration factors of artificial ageing have been studied for decades, but general formulas or equations and rules ready for practical applications have not been established. This kind of knowledge would be very useful as the basis of qualification testing.

Another issue regarding the ageing of polymer materials is the vast number of different compounds and detailed formulations available on the markets. In addition, the detailed formulations are not usually commonly available. It is known that even if the basic polymer remains the same – for example, due to different additives – the ageing behaviour of the polymer material might change significantly. This further complicates the qualified lifetime management and traceability of polymer materials. It would be highly beneficial to have the means of determining the effects of change of, say, a certain additive, on the ageing behaviour without the need for repeating the entire, time-consuming type test programme including the artificial ageing treatments. In addition, a relatively simple test method for verifying that certain polymer compound matches the qualified one would have a lot of practical applications.

As for ageing management and the condition monitoring of electrical and I&C components installed in nuclear power plants, non-destructive field test methods are considered as having the best practical importance. One interesting aspect of ageing management is using the concept of qualified condition instead of qualified lifetime, which means that in type testing of a component, during (or at least after) the artificial ageing treatment, before the possible accident or design basis event tests, a certain condition indicator representing the ageing deterioration of the component/materials is measured, and during the operation of the component at the plant the same condition indicator is measured at certain intervals to verify that the ageing status remains above the qualified condition. Investigating the reliability of different condition indicators for qualified condition with a relatively simple component (e.g. a cable) in practice could provide some useful information for ageing management in general.

Another R&D area is the ageing of coatings. EPDM (ethylene propylene diene monomer) coatings have been used, for example, in pool structures.

Water chemistry

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 the old and new nuclear power plants, intermediate circuits, component cooling circuits, generator water-cooled circuit 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. Water chemistry issues are linked to materials' performance as a whole because the water chemistry of the system impacts also on the corrosion of materials. Corrosion in turn plays an important part in, for example, the initiation of cracks and the formation of corrosion products.

One of the topics in the area is the activation build-up on the primary circuit surfaces and the effect of the water chemistry regime and different surface conditions in existing and new plants. Regarding new plants, the passivation procedure of primary circuit surfaces during the Hot Functional Testing (HFT) period is of high importance in reducing the activity build-up during the following operational periods. Therefore, the optimisation of the procedures and water chemistry regime used during HFT 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 the operational periods and reduction of activity release and impurity enrichment during transients forms another research area relevant to reducing activity build-up.

Impurities and their enrichment in areas of restricted flow form a threat to the integrity of pressure boundaries of both BWRs and PWRs. In the secondary side of PWRs, stress corrosion cracking (SCC) caused by enrichment of impurities due to boiling continues to be the main cause of failure of steam generators. In BWRs, for example, chloride and sulphate transients are suspected of enhancing stress corrosion cracking in, for example, dissimilar welds and pressure vessel steel under cladding. Research work aimed at understanding the mechanisms of impurity enrichment and developing models for the phenomena is internationally recognised as a relevant area.

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 can even become forbidden due to its toxicity. Alternative water chemistry regimes replacing hydrazine in PWRs are actively sought out and form another possible research topic.

Small and medium size reactors (SMR) are currently being developed worldwide. The water chemistry of these reactors has not been decided, and may differ markedly from current operating reactors. This is an area foreseen as a research item that needs to be at least followed carefully.

Automation systems

Research has been carried out on the ageing of relay components. Traditional technology usually relies on primary evidence based on experiments made through testing, inspections and mechanical sampling. An interesting research topic is the ageing of the polymer parts of these components (see polymer materials research above) in addition to the metallic parts and components in relevant environmental conditions. It would be useful to know the ageing and type testing conditions also for the new parts that will replace the older aged ones. New digital automation has different ageing phenomena, technology ageing.

Design and ageing management

Design and ageing management of at least new materials and structures in mechanical and civil engineering should be identified and supported by research. A better understanding is needed between traditional design criteria with corresponding design margins and design extension conditions (DEC) with a safety and security interface. Corresponding supportive research in line with internal and external hazards and events is needed.

3.5.3.2 Non-destructive examination and assessment methods

The importance of developing non-destructive examination methods (NDE) was highlighted in the assessment of the SAFIR2018 research programme. Research areas for metallic structures include, among others, the study of the inspectability of fatigue fractures with NDT methods and, in particular, the verification of the reliability and detection probability of the related observations and the creation of probability or detection (POD) graphs. A new topic where NUGENIA collaboration is possible would be the research on magnetite accumulation in the steam generator, which, as a topic, is closely related to the research of the effect of water chemistry in the steam generator. In addition, POD modelling should be developed for complex objects, such as reactor pressure vessel assembly and dissimilar metal joints. One of the goals for the metallic NDE is standardisation.

The goal in the programme is also to apply NDE technologies to concrete structures with a reliability that corresponds to that attained with metal structures. Although concrete as a porous material and implemented reinforcement as compound materials constitute a diversified research object, the NDE methods applied there are principally the same as with metal structures. For example, research needs include the reliability of results obtained with NDT methods on concrete structures and the suitability of different methods for the life cycle management of nuclear power plant structures. In concrete research, there is a connection to the National Research Programme on Nuclear Waste Management (KYT) where the long-term characteristics of concrete are researched experimentally under final disposal conditions.

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 (NDT) is carried out during the in-service lifetime. However, current NDT faces several challenges: the accuracy of the test devices, the compatibility of different NDT methods with the concrete structures and their deterioration mechanisms, the global uniformity of the NDT test methods and creditability of the test results and analysis. As a result of NDE tests for reinforced concrete structures, the following are of interest: the level of reinforcement corrosion and recognising and localising voids behind liner plates, such as in pools and tendon cable ducts. It is of interest to know the severity of reinforcement corrosion and when it is necessary to take remedial actions.

Research on non-destructive test methods of polymer materials is also considered important. It could provide new information on ageing of, for example, electrical and I/C components in nuclear power plants.

3.5.3.3 Structural safety analysis and preparation for new technologies

In line with the SAFIR2018 programme, the areas of focus in computational assessment of structural integrity are various plant transient situations and the development of structural analysis methods, and determining the loads caused by various process situations in a more realistic way. Examples of these are thermal stress and heat stress in fluid-structure interaction analyses, and realistic assessment of residual welding stress, also considering the load and effect of operating time. In the future, instructions must also be given for the commonly acceptable usages of the related complex software, and for calculation methods in general. Event information databases should be developed and maintained for calculation, as they would enable the statistical processing of the phenomena in the plant's life cycle management.

Determining the fracture-mechanical parameters of radiated material based on experiments involves continuous development of the calculation methods. The established examinations based on the Master curve concept and their development will also retain their central role in the future. The development of numerical analysis methods requires more accurate material characterisation methods as well, and this means that experimental research must continue.

At present, the safety classified concrete structures of nuclear power plants, particularly the containment building, are designed to withstand considerable unexpected loads. Ensuring the load tolerance requires reliable specifications of the structure's integrity. For containment buildings, the most important methods are stress, deformation, temperature and humidity measurements using fixed and temporary measurement devices. In this respect, it is important to follow the development of international standards in the field, which, at the moment, does not include how probabilistic structural calculations have to be performed.

The SAFIR2018 programme has covered experimental impact tests on reinforced concrete slabs for assessing the bending and perforation of a straight wall. In addition, computational methods have been developed and validated. Dedicated impact tests will be carried out. The development of modelling methods and techniques for impact loaded structures will continue. Numerical methods will be validated using experimental data and benchmark studies.

Vibration phenomena affecting design and ageing management need to be understood better. The source of vibration can be internal from the plant process, including acoustic vibrations, and external, from an earthquake or airplane crash.

Qualification against vibrations is challenging and require competent people within research, design and the operation of utilities.

The dimensioning of structural fire safety is based on assumptions concerning fire development, performance measured under standardised conditions and the performance requirements set by plant solutions. There are computational methods for the functional dimensioning of structural fire safety, but the dimensioning adheres to a tradition that dates back decades. The modelling and simulation methods should be developed so that the behaviour of real structures and their components during different kinds of fires can be assessed computationally. The methods should be such that they can be combined with probabilistic fire simulations in order to create a design PRA connection. Also defence in depth of fire protection should be acknowledged in order to ensure the clear design and PRA against the spread of fire.

More interaction with other research areas of the SAFIR2022 programme should be created in the field of structural integrity, such as the assessment of the safety significance of phenomena and structures with respect to overall plant safety. In addition, the utilisation of international research programmes should be improved. New construction methods and methodologies will be followed: steel-concrete structures, modular construction, the assessment of various regulations and standards in nuclear power plant structures, probabilistic structural analysis and design needs and more broad-scale utilisation of experimental equipment.

The following research topics have been recognized items that could possibly provide useful information:

FEM coupling for structural analysis:

- combination of fluid dynamic analysis with structural response analysis
- combination of temperature conductivity/radiation analysis with structural response analysis
- PSA level 2 analysis

Traditional tools for conservative safety analyses + high-fidelity tools for best-estimate analyses:

- development of validated procedure
- methodology for design and design extension conditions analysis
- (material, structures, loads and load combinations taken account phase differences and frequency of occurrence)

Typical structural analysis, if any:

- Core catcher
- IVR (In Vessel Retention)
- Containment tightness also PRA level 2 point of view
- Vibration analysis of structures, pipelines and HVAC channels, including acoustic vibration

External hazards, structural response and equipment qualification

- PSA level 2 analysis, containment
- Seismic analysis
- APC
- Explosion analysis

Ageing management spent fuel pool from PRA level 2 point of view

Preparation for new technologies (SMR, etc.).

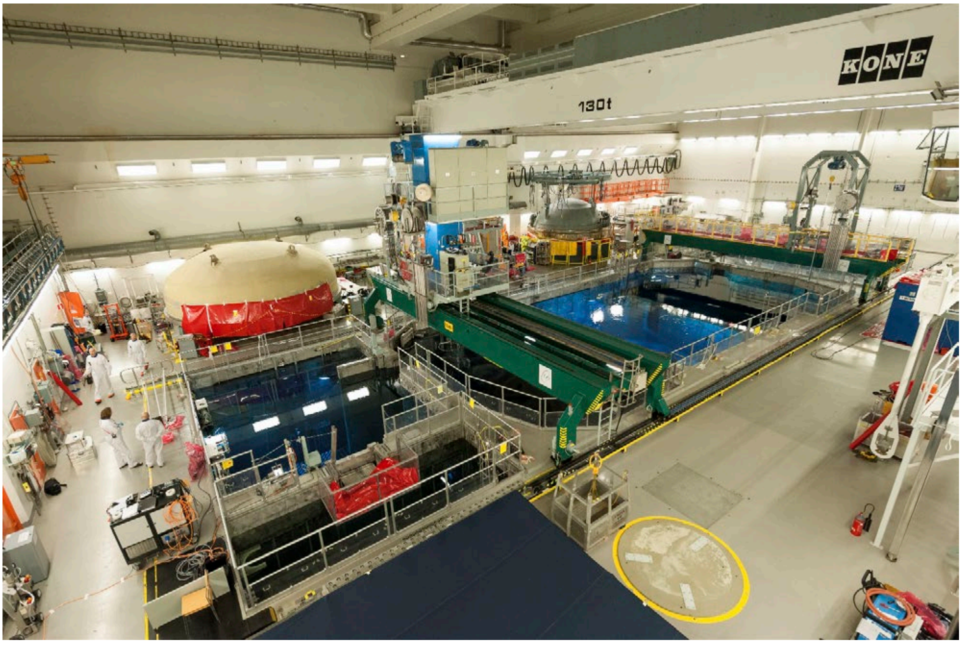
3.5.3.4 New material solutions

Additive manufacturing

Although the nuclear industry has very high quality and certificate requirements, it has recognised the potential benefits of additive manufacturing (3D printing) and work is ongoing to expand the standard procedures and to deepen understanding of material-process-property relationships including irradiation performance. Additive manufacturing is still in its very early stage of development with regard to the characterisation of mechanical properties and qualification practices starting from the qualification of components. Much work is needed before additive manufacturing can be used in the manufacture of NPP components – the final objective being the introduction of additive manufacturing in nuclear design codes. It has been recognised that both additive manufacturing and Hot Isostatic Pressing methods are both essentially powder metallurgical, near net shape manufacturing processes, which have differences but also some common features. Research on these evolving technologies is needed to pursue the manufacture of NPP components in the future.

The implementation and licensing of future plant projects or replacing new components may cause a research need concerning new materials and structural solutions and new production techniques. Possible new manufacturing technologies or new materials (e.g. stellite replacing materials, nickel-based alloys, nitrogen alloyed austenitic stainless steel) may become important areas of study. Changes in manufacturing techniques and in structural design are also a challenge for component lifetime management.

Figure 3.5 Annual maintenance at the Olkiluoto plant (source: TVO).



3.6 Research infrastructure development

3.6.1 Finnish nuclear safety infrastructure in the global network and market

The safety assessment of nuclear power plants requires deep knowledge concerning the physical processes taking place inside the plant systems, structures and components. Such knowledge ultimately rests on representative experimentation and physical modelling, which allows the development, verification and validation of computational tools for safety assessment. A similar understanding is also needed for the assessment of operational safety and plant ageing. Moreover, decades of experience demonstrates that novel safety issues may emerge, often as a consequence of phenomena originally misunderstood, or forgotten over time. Examples of such major events include the Barsebäck ECCS strainer issue in 1992, Davis Besse hole-in-the-head in early 2000, the Paks fuel damage incident in 2004, the Forsmark emergency power supply failure in 2006, and the Fukushima meltdowns in 2011.

Therefore, there is a need for up-to-date research capabilities that can satisfy the needs of both existing and future power plants and other nuclear facilities. In addition to infrastructure related directly to the safe use of nuclear power plants, research capabilities that support the ageing management of the plants, interim storage and final disposal of used fuel are also important (interfacing with KYT2022).

When the research on the power plants in operation or under construction is combined with their long service life and the subsequent decommissioning period, as well as the final disposal of fuel, the time span for research infrastructure after commissioning a new plant is at least 100 years. On the basis of operating experience, including the Fukushima accident, safety functions must be developed further and preparations made for rare initiating events and combinations of events, as well as for emerging (or re-emerging) safety issues. To meet this requirement, Finland must possess sufficient infrastructural preparedness for its own experimental and computational activity. Domestic infrastructure and experimental research is vital for the maintenance and enhancement of national competencies. Moreover, it can be used to leverage international experimental capabilities for Finnish needs, The strong development phase in SAFIR research started with the development of the VTT research capabilities realising the VTT Centre for Nuclear safety, thus concentrating in VTT and the Otaniemi area. The next phase is to continue the development of the LUT facilities in Lappeenranta. Further, there is a need to develop the areas that can be common for SAFIR and KYT research, thus preparing the way for the combined programme from 2023.

3.6.2 The VTT Centre for Nuclear Safety

The VTT Centre for Nuclear Safety and its new hot cell facilities was constructed and licensed for operation over the period from 2013 to 2018. With full licensing achieved in 2018, the new facility will transition to full research and testing operations over the SAFIR 2022 period. During this period it is important to continue to adapt the equipment and develop the handling processes and tools for executing particular research activities presented by the needs of topical research projects. Support of the infrastructure development in this manner is important for establishing a portfolio of means for executing the nuclear safety research activities, enabling those research projects to focus on their core scientific goals, rather than on the practicalities of adapting the infrastructure to their technical needs.

At the same time, the decommissioning of the old research reactor and radiological facilities has transitioned from clean-up and removal of equipment and legacy waste, to the more serious work of decontamination and dismantling. The confluence of these two research infrastructure processes has revealed the importance of having long-term waste handling strategies, and planning for decommissioning already in the commissioning phase. The importance of such recognition is also relevant in the context of converging the SAFIR and KYT research programmes.

As a brand new, clean and modern facility, the VTT Centre for Nuclear Safety should utilise this historical infrastructure renewal opportunity to develop the devices and processes necessary to minimise the operational and decommissioning waste already from the outset. Even if nation-level negotiations are underway to secure a long-term disposal solution for decommissioning waste from the FiR1 test reactor and old radiological facilities, it is in all stakeholders' interest that the ultimate volume of future waste is minimised to as little as is reasonably achievable. The means for minimising the accumulation of contamination in the first place, effectively decontaminating in the second place, and reducing the volume of radioactive waste in the third place are all steps that can bring benefits not only to the operations of the new facility but also to the decommissioning of the old facilities, and perhaps even to the future decommissioning of NPPs. A thorough waste handling programme is also an essential component for enabling collaborative opportunities nationally between VTT and universities, and particularly across national borders where trans-shipment of anything that could be interpreted as radioactive waste is strongly frowned upon, and often prohibited by legislation. Finally, in addition to effectively managing the waste stream, it is important to establish the other means for ensuring the safe utilisation of the facilities beyond VTT; first, within Finland through access by universities, and second, internationally through active participation in research infrastructure networks that promote access by externals. On the European level, enabling access is also strongly promoted, particularly within the cost-heavy nuclear research infrastructures, and it is essential for the Jules Horowitz Reactor becoming operational for irradiating and then characterising test materials in a collaborative manner.

The construction of VTT Centre for Nuclear Safety, which has new hot cell facilities and other facilities and equipment needed for research on nuclear technology materials, commenced in 2013. Radiological commissioning of the facility was completed in 2017, and the ramp-up of the hot cell utilization is still ongoing. The research to be carried out at the centre is on GEN II– IV reactors, fusion energy and nuclear waste management. The existence of shared facilities and equipment will promote the synergy of Finnish research on existing and future reactor concepts.

Another topical issue is the utilisation of the decommissioned Barsebäck reactor in Sweden for international research projects before it is dismantled in 2020.

It is expected that by the end of 2022 we will have:

- A fully operating Centre for Nuclear Safety radiological facility and hot cell providing a diverse array of services for all national stakeholders, with a minimal waste stream.
- Capacity that is effectively utilised through access agreements with domestic universities and selected international partnerships.

3.6.3 Thermal hydraulic facilities at LUT

Domestic capability to build, run and operate thermal hydraulic test facilities is essential for gaining a better understanding of the processes in nuclear power plants in all phases of a plant's lifetime. In the design and licensing phases, the performance of new technologies (novel safety system designs, core catchers, etc.) needs to be independently verified. In addition, the resolution of emerging safety issues (Barsebäck, Davis-Besse, Paks, Fukushima) requires facilities, devices and testing procedures that can be developed only by professional skilled staff. Ageing processes and operational loads of the plant systems have to be known to allow the long-term operation of the plants (licence renewals). Generally, for understanding the phenomena and processes already known, and especially those that are previously unforeseen, there has to be an environment that enables studies on these processes also experimentally.

New and advanced measuring techniques allow for more detailed and accurate data to be collected from the test configurations also in 3D geometries. In addition to gaining experience and understanding the phenomena in the processes from the tests, the data supports the safety analysis code development and validation, also for CFD analyses.

The LUT thermal hydraulic testing infrastructure and the operating staff aim to be capable of constructing, instrumenting and operating representative models of all phenomena of interest to stakeholders (mainly the power companies and the regulator). Upgrading the research infrastructure of nuclear engineering at LUT began in 2016, with the first steps of the current infrastructure being funded by the Academy of Finland. In the NextGenTH project (2016–2018) a vision of a flexible thermal hydraulic research environment has been presented and the basic operating parameters have been decided together with stakeholders. The flexibility is based on modularity and the innovative use of the components (modules) such as pressure vessels, heating modules, heat exchangers, etc. The first configuration of this research environment (MOTEL) will be a model of a SMR (Small Modular Reactor).

A project proposal for the continuation of the FIRI project has been submitted to the Academy of Finland. The proposal aims to supplement MOTEL with further interchangeable modules to represent either an SMR containment or a PWR. The funding period in the application is for 2019–2021.

Thermal hydraulic infrastructure relies on the instrumentation, knowledge of using it as per the instrument design, but also finding innovative and new ways of using measuring devices. The measurement techniques to be introduced include optical fibre-based temperature or strain profile determination, and expanding the use techniques already explored in SAFIR2018, namely Wire Mesh Sensing and Particle Imaging Velocimetry, both of which have already shown great promise and proven their usefulness.

High-performance calculation servers suitable for high-fidelity CFD analyses form an important part of the thermal hydraulic infrastructure at LUT. They are utilised both to the qualification and validation of the CFD models against data obtained from experiments and to the actual design of experiments.

Innovative development must be continued in areas considered important in order for Finland to retain the capacity to carry out experiments regarding the thermal and flow technology of nuclear reactors even when they concern new and unexpected phenomena.

It is expected that by the end of 2022 we will have:

- a research environment capable of studying experimentally and numerically any thermal hydraulic problem that may arise in the nuclear power plants in Finland, or candidate plants considered by the Finnish stakeholders;
- the capability to design, construct and operate thermal-hydraulic test facilities and associated measuring systems;
- two alternative MOTEL configurations (MOTEL SMR and MOTEL TBD);
- separate-effects test sections for topics of current interest, such as ageing related studies or sump/strainer performance assessment, run either as part of MOTEL or independently;
- state-of-the-art measuring techniques available for data collection and visualisation – pointwise, 1D-, 2D-, 3D-field mapping, high-speed photography.

3.6.4 Jules Horowitz Materials Testing Reactor

In the future, the forthcoming Jules Horowitz materials testing reactor will be one part of the Finnish nuclear infrastructure, even though it is located in France. The construction of the JHR will be finalised during the SAFIR20122 programme period (first criticality in 2022) and in parallel with that the start of the operational phase and the first experimental programmes will be planned by the international JHR consortium. The JHR Governing Board nominated three working groups (Fuel, Materials and Technology WGs) to collect together the scientific topics already in 2012. Since then, these WGs have been planning the first programme already for the pre-JHR era. Currently, the plan is for the pre-JHR fuel studies to be carried out in connection with the OECD/NEA, and the first material programme in the H2020/EURATOM project in connection with the European Nuclear Education Network (ENEN). In the fuel programme, the target will be in "Quantifying clad thermomechanical load mechanisms during LWR transients", whereas in the material programme the main focus will be in "Standardization/harmonization of facility usage and best practices concerning mechanical testing of irradiated materials and microstructural characterizations". Even though being "modest" programmes, the starting and organisation of the internal JHR consortium co-operation is very important at this stage in order to get prepared for the actual reactor programmes starting in 2023 and later.

In Finland so far, participation in the JHR WGs has been mainly VTT's and partly Fortum's responsibility. However, in the future, and already during the SAFIR2022 programme, operation planning needs to involve the entire Finnish consortium that owns the share of the JHR experimental capacity. The natural home base for the JHR operation phase is the SAFIR2022 programme and other programmes after it. Therefore, in the planning of the projects for this programme the possibilities for co-operation with the JHR community should be taken into consideration as well.

It is expected that by the end of 2022 we will have:

- The Finnish in kind construction project producing real equipment to the JHR reactor is finished and the first pre-JHR experimental programmes are running for fuel and material studies.

- Finnish participation via the SAFIR2022 programme is active.
- In parallel, the planning of the first actual JHR experimental programme is on-going and even finished before 2022.
- The Finnish nuclear community participates in the "JHR School" by having younger experts as students and getting networked there. '
- The co-operation between VTT CNS and the JHR has been established via the programmes.

3.6.5 Other national infrastructures

The Reactor Materials Research Group began in the early 1970s under KTM (≈ currently the MEAE) but was soon organised to VTT Metals Laboratory, which became a major international player in the field of NPP pressure boundary material performance and reliability in realistic conditions. Today, the experimental facilities are located in the CNS and the underground Research Hall 1. The CNS is dedicated to studying reactor internals, RPV and other active materials. However, a major part of the experimental research on fracture, fatigue, corrosion, wear and other ageing phenomena related to NPP primary and secondary side structures and facilities used in the qualification of different polymeric components are currently located in Research Hall 1. This research infrastructure has grown an internationally rare infrastructure for multi-disciplinary materials and components research, including also the inspection and long-term safety of materials and concepts used for spent fuel disposal.

Currently, the VTT Impact test facility is unique in the world. The current project partners have expressed a need for more realistic tests. In order to study the dynamic behaviour of reinforced concrete structures that are more close to real life scenarios (airplane crashes into NPPs) the capacity of the existing test facility needs to be updated. In particular, the missile mass and velocity needs to increase and larger and more realistic target structures need to be implemented. As far as knowledge transfer is concerned, maintaining sufficient know-how is a key issue in utilising the VTT Impact test facility.

It is expected that by the end of 2022 we will have:

- An upgraded impact test facility in use and it enables experiments that are very close to the real life scenarios, such as containment wall perforation by an aircraft engine shaft.

4 Summary

The safe use of nuclear power requires national expertise based on high-quality scientific research. Chapter 7a of the Finnish Nuclear Energy Act, which came into force in 2004, sets the objective of national nuclear safety research: to ensure that if new matters related to the safe use of nuclear power plants should arise, the authorities possess sufficient technical expertise and other competence for determining the significance of those matters without delay. The aim of the nuclear safety programme planned for 2019–2022, under the name SAFIR2022, is to ensure expertise particularly in topics where no research would otherwise take place in Finland.

The programme is funded by the Finnish State Nuclear Waste Management Fund (VYR), as well as other key organisations operating in the area of nuclear energy. The annual funding of the SAFIR2018 programme has been in the order of EUR 10 million annually. In the new programme, the goal is to keep Finnish funding at the same level or increase it slightly.

Several licensing and safety evaluation projects will take place during the SAFIR2022 programme period: Olkiluoto 3's operating licence, Fennovoima's construction licence for Hanhikivi 1, periodic safety reviews of Loviisa 1 and 2. Significant modernisation projects will be carried out for Loviisa 1 and 2 as well as the Olkiluoto 1 and 2 plant units. The SAFIR2022 programme works as an environment that provides nuclear safety researchers with a possibility for in-depth training in the research projects and that also facilitates the training of young new experts.

The significance of a high scientific level of national research is emphasised as activities become more international. The SAFIR2022 programme is an important channel for international co-operation. Experimental environments are particularly expensive and, despite significant Finnish investment in the past and coming years, participation in international development projects and the utilisation of international infrastructure are necessary in order to maintain the high quality of national activities.

The research content and procedures of SAFIR2022 have taken into account the international assessment of the SAFIR2018 research programme ordered by the MEAE and implemented during the spring 2018 [3]. The recommendations of the research strategy for the nuclear power sector [5] and the report of the national competence workgroup on the nuclear energy field [4] were already taken into account in the planning of SAFIR2018. The competence survey reported in [4] was updated for 2017 situation in the SAFIR2018 administration project.

The administrative structure of SAFIR2022 follows that of SAFIR2018. The goal of the structure in SAFIR2018 was to improve administrative work efficiency and reduce it in projects and groups steering the projects. The SAFIR2022 programme's operating model consists of a Management Board and four research area steering groups working under it. Each project is associated with a reference group that concentrates on scientific and technological guidance.

The research planned for the SAFIR2022 programme has been grouped into four research areas: (1) Overall safety and a systemic approach to safety, (2) Reactor safety, (3) Structural safety and materials, and (4) Research infrastructure.

Overall safety and systemic approach to safety collects a wide range of nuclear safety research areas that overarch between several topics, as well as topics affecting the nuclear power plant as a whole. Such topics include the concept of overall safety itself, organisational issues, automation architecture, control room design and operations, human factors, external hazards, safety and security interfaces, electrical systems, setting the safety requirements, and controlling the plant design throughout its lifetime.

Reactor safety research focuses on the development of experimental and computational methods aimed at ensuring that a nuclear facility and its systems are able to implement the safety requirements set for them. The research questions focus on the fundamental safety aspects and on an understanding of the behaviour of nuclear fuel, plant processes and plant systems in both normal and abnormal situations, including phenomena relevant to accident progression and the resulting consequences. In addition to general method development for complex multi-physics phenomena, the tools need to be validated and the uncertainties managed. Important topics are also severe accident analysis and management, internal and external hazards, including the fire risks analysis and phenomena related to the climate change and fuel research.

The aim of the research on structural safety and materials is to increase knowledge that supports the long-term and reliable use of our 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 devices and structures and the correctly timed management of their progress. Attention should also be paid to the utilisation of structure- and device-specific ageing information and the operative capability of the devices and structures in exceptional conditions. The research topics include ageing (metallic, concrete, polymer, water chemistry, automation systems), non-destructive testing (NDT, metallic and concrete), structural safety analysis, preparation for new technologies and new material solutions.

Domestic infrastructure is vital for the maintenance and enhancement of national competencies. It is also useful for leveraging international experimental capabilities for national needs. The safety assessment of nuclear power plants requires deep knowledge about physical processes taking place inside the plant systems, structures and components. Such knowledge ultimately rests on representative experimentation and physical modelling. A similar understanding is also needed for the assessment of operational safety and plant ageing. Up-to-date research capabilities should satisfy the needs of both existing and future power plants and other nuclear facilities. The strong infrastructure development phase in the SAFIR programmes started with the development of VTT research capabilities realising the VTT Centre for Nuclear Safety. The next phase is to continue the development of thermal hydraulic facilities at Lappeenranta University of Technology (LUT).

A 17-person planning group appointed by the MEAE and several other experts have actively participated in the preparation of the Framework Plan. The planning group included members from the Ministry of Economic Affairs and Employment

(MEAE), the Radiation and Nuclear Safety Authority (STUK), Fennovoima Oy, Fortum, Teollisuuden Voima Oyj (TVO), Aalto University, Lappeenranta University of Technology (LUT), and Technical Research Centre of Finland Ltd (VTT). The organisations participating in the planning represent the end users of the results and research organisations.

The Framework Plan presents the research topics that the planning group considered important in June 2018. In addition to four-year-project proposals, one- or two-year proposals are also expected. As already in SAFIR2018, there will be so-called small study projects on research topics not included in the approved proposals. The volume reserved for the small study projects ordered annually by the Management Board will be increased and the amount of one- and two-year projects is expected to increase. The goal is to help start new projects on new topics during the programme period.

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Appendix 1: SAFIR2022 Nuclear Safety Assessment Capability Model

Area	Elements	Note
Human resources	OTR competences nuclear specific area, no bottle necks, redundancy nuclear related areas, all important areas covered, competitive partnerships	assessment and indicators for each year in connection to funding decisions
Tools	appropriate coverage of validated tools agreements on use of international tools excellence/very good /good	list of tools goal/status
Laboratories	VTT CNS LUT JHR international cooperation active jointly funded research projects in nuclear safety research infrastructure network	research project, capacity in use and experiments international co-operation; projects and experiments volumes
Career development and training	degrees, interface with PhD program trainees recruitment by stakeholders' organizations personnel (review every second year)	indicators assessment;
Networking	active participation in international research projects attractiveness: experts and students jointly founded projects: number and volume external funding presentations at conferences	indicators
Knowledge management and assets	data assets deliverables: publications …. …….	list of assets indicators R€=deliverable/ funding
Research general	funding publications impact assessment research improvement (quality, perform research program, improvement) IP assets etc.	indicators assessment indicators/ description

Overall assessment of research: RG/SG/or the whole SAFIR2022 programme.

Grade	Description
Excellent	Extremely strong performance at the level of international leadership. Groundbreaking research with transformative impact on the field. Essentially no weaknesses.
Very good	Very strong performance and innovative research at an exceptionally high international level. Significant impact on the field. Some negligible or minor weaknesses.
Good	Strong research at the level of national leadership. Several minor weaknesses.
Fair	Overall performance at a nationally competitive level with solid potential for impact on the field. Several minor and at least one moderate weakness.
Poor	Unsatisfactory overall performance. At least one major or two moderate weaknesses.

National Nuclear Power Plant Safety Research 2019–2022

SAFIR2022 Framework Plan

The public nuclear safety research programmes provide the necessary conditions for maintaining the knowledge needed for ensuring the continuance of safe and economical use of nuclear power, for the development of new know-how and for participation in international cooperation. The Finnish organisations engaged in research in this sector have been an important resource that the various ministries, the Radiation and Nuclear Safety Authority (STUK) and the power companies have had at their disposal.

The Ministry of Economic Affairs and Employment (MEAE) appointed in November 2017 a group to write the Framework Plan for the new programme. This report contains a proposal for the general outline of the programme, entitled SAFIR2022 (SAfety of Nuclear Power Plants – FInnish National Research Programme). The plan has been prepared for the period 2019–2022, but it is based on safety challenges identified for a longer time span as well. The research programme is strongly based on Chapter 7a of the Finnish Nuclear Energy Act.

The construction and planning of new power plant units have increased the need for experts. At the same time, the retirement of existing experts has taken place and retirements are continuing. Active long-term research still plays a key role in the education and training of new experts.

The Framework Plan aims to define the important research needs related to safety challenges. The programme also aims to maintain and increase know-how in those areas where no significant changes occur but in which research activities are the precondition for the safe use of nuclear power.

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