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Finnish Research Programme on Nuclear Waste Management KYT2022

Framework Programme for the Research Period 2019–2022

Ministry of Economic Affairs
and Employment of Finland

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Abstract

KYT2022 is the research programme of the Ministry of Economic Affairs and Employment, where the objective is to ensure that the authorities have sufficient levels of such nuclear expertise and preparedness that are needed for comparison of different nuclear waste management methods and technologies. Research directly related to licensing applications belongs in other programmes by the authorities and those responsible for nuclear waste management.

The starting point for public research programs on nuclear safety is that they create the conditions for maintaining the knowledge required for the continued safe and economic use of nuclear power, developing new know how and participating in international collaboration. Nuclear research organizations in Finland have been an important asset for the ministries, Radiation and Nuclear Safety Authority (STUK), power companies and Posiva.

The content of the KYT2022 research programme is composed on nationally important research topics, which are the safety, feasibility and acceptability of nuclear waste management. The research programmes aim for large, coordinated topics that can have one or multiple year duration. KYT2022 research programme also functions as a discussion and information-sharing forum for the authorities, those responsible for nuclear waste management and the research organizations, which helps to make use of the limited research resources. The programme aims to develop national research infrastructure, ensure the continuing availability of expertise, further high-level scientific research and increase general knowledge of nuclear waste management.

The framework programme has been authored on behalf of a planning group named by the Ministry of Economic Affairs and Employment. The framework programme is valid for 2019–2022.

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Referat

KYT2022 är arbets- och näringsministeriets forskningsprogram, vars mål är att säkra, att det till myndigheters förfogande finns tillräcklig och omfattande tillgång till sådan kärnteknisk sakkunskap, som behövs för att jämföra olika tillvägagångssätt och metoder för kärnavfallshantering. Den forskning, som direkt hör till övervakningsplikten av kärnavfallshantering och till tillståndsansökningar, hör till myndigheternas och de avfallshanteringsskyldigas övriga program.

Utgångspunkten för programmen inom kärnsäkerhetsforskning är att de skapar förutsättningar för upprätthållande och utveckling av sådant kunnande, samt deltagande i internationellt samarbete, som en fortsatt säker och ekonomisk användning av kärnkraft förutsätter. De organisationer, som bedriver forskning inom detta fackområde har varit en stark tillgång, som olika ministerier, Strålsäkerhetscentralen (STUK), kärnkraftsbolagen och Posiva har kunnat utnyttja.

Innehållet i forskningsprogrammet KYT2022 består av nationellt viktiga forskningsmål, det vill säga kärnavfallshanteringens säkerhet, genomförbarhet och acceptans. Inom forskningsprogrammen strävar man till omfattande, koordinerade helheter som kan vara ett- eller fleråriga. KYT2022 forskningsprogrammet fungerar också som ett diskussions- och informationsforum för myndigheter, de organisationer som verkställer kärnavfallshantering och forskningsinstitutionerna, varvid man skapar förutsättningar för användning av de begränsade forskningsresurserna. Strävan är att inom programmet befrämja utveckling av det nationella kunnandet, av infrastrukturen, säkra fortlöpande tillgång till sakkunskap, befrämja högklassig vetenskaplig forskning samt öka kunskapen inom kärnavfallshanteringens fackområde.

Ramprogrammet har utarbetats av en planeringsgrupp som tillsatts av arbets- och näringsministeriet. Ramprogrammet täcker åren 2019–2022.

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Tiivistelmä

KYT2022 on työ- ja elinkeinoministeriön tutkimusohjelma, jossa tavoitteena on varmistaa, että viranomaisilla on saatavilla riittävästi ja kattavasti sellaista ydinteknistä asiantuntemusta ja muita valmiuksia, jota tarvitaan ydinjätehuollon erilaisten toteutustapojen ja menetelmien vertailuun. Ydinjätehuollon valvontavelvollisuuteen ja lupahakemuksiin suoraan liittyvä tutkimus kuuluu viranomaisten ja jätehuoltovelvollisten muihin ohjelmiin.

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

KYT2022 tutkimusohjelman sisältö koostuu kansallisesti tärkeistä tutkimuskohteista, jotka ovat ydinjätehuollon turvallisuus, toteutettavuus ja hyväksyttävyys. Tutkimusohjelmissa pyritään laajoihin, koordinoituihin kokonaisuuksiin jotka voivat olla yksi- tai monivuotisia. KYT2022 tutkimusohjelma toimii myös viranomaisten, ydinjätehuoltoa toteuttavien organisaatioiden ja tutkimuslaitosten välisenä keskustelu- ja tiedonvälitysfoorumina, jossa luodaan edellytyksiä rajallisten tutkimusresurssien hyödyntämiselle. Ohjelmassa pyritään edistämään kansallisen osaamisen ja tutkimusinfrastruktuurin kehitystä, varmistaa asiantuntemuksen jatkuva saatavuus, edistää korkealaatuista tieteellistä tutkimusta ja lisätä yleistä tietämystä ydinjätehuollon alalla.

Puiteohjelma on laadittu työ- ja elinkeinoministeriön nimeämän suunnittelutyöryhmän puolesta. Puiteohjelma on laadittu vuosille 2019–2022.

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FOREWORD

The Ministry of Economic Affairs and Employment (MEAE) of Finland is launching the Finnish Research Programme on Nuclear Waste Management (KYT2022) for 2019–2022. The project call for the first year of the research programme will start in September 2018. The project call is open for all projects related to research, research infrastructure or further education.

The KYT2022 framework programme contains a description of the programme's research objectives and areas of focus. It also includes descriptions of the programme's actors and organization. The objective of the research programme is to ensure that the expertise in the area of nuclear waste management is available primarily for the use of authorities when evaluating different implementation methods and processes according to the objectives defined in the nuclear energy law. In addition, the goal of KYT2022 research programme is to support and complement the research programmes of the waste management organizations, and to further develop communication between authorities, waste management organizations and researchers.

The KYT2022 research programme is scheduled at an interesting period in the Finnish nuclear waste management field. During this programme period, as timetabled, Posiva will take a major leap towards starting the final disposal of spent nuclear fuel. This is also a significant step internationally. The interest towards Finnish know-how abroad has been great and it is expected to increase further. The interest towards Finland is an opportunity that could be utilized by networking and participating to international research projects. The framework programme describes the main features of the international networking of Finnish organizations.

After the end of the KYT2022 research programme, the Finnish Research Programme on Nuclear Waste Management (KYT) and the Finnish Research Programme on Nuclear Power Plant Safety (SAFIR) will merge into one. Through this merger, the research subjects left at the boundary of these programmes, such as the decommissioning of nuclear facilities and the intermediate storage of spent fuel, will be better taken into consideration. In addition, the use of the entire nuclear facility of Posiva will begin and implementation of the long planned facility will mark a new phase in the field of nuclear safety research. The development of new technologies might also benefit from the common programme.

The framework programme has been prepared by a planning group appointed by the Ministry of Economic Affairs and Employment on September 22nd 2017. The planning group members in the role of experts are as follows: Jaakko Leino (Radiation and Nuclear Safety Authority, STUK), Mikko Paunio (Ministry of Social Affairs and Health, STM), Susanna Wähä and Sami Rinne starting on January 10th 2018 (Ministry of the Environment, YM), Linda Kumpula (TEM), Pasi Kelokaski (Fortum Power and Heat Oy), Arto Kotipelto (Teollisuuden Voima Oyj, TVO), Anne Kontula (Posiva Oy), Heikki Hinkkanen (Fennovoima Oy) and, starting on May 3rd , Suvi Karvonen (VTT Technical Research Centre of Finland Ltd) as expert members. The deputy members were Mia Ylä-Mella (STUK), Jari Keinänen (STM), Kati Vaajasaari (YM), Jorma Aurela (TEM), Olli Nummi (Fortum Power and Heat Oy), Antti Tarkiainen (TVO), Pekka Kupiainen (Posiva Oy) and Tuire Haavisto (Fennovoima Oy). Kari Rasilainen (VTT) was secretary to the planning group. The English version of the framework programme was prepared at VTT by Aku Itälä, Suvi Karvonen and Kari Rasilainen.

Helsinki, September 2018

Ministry of Economic Affairs and Employment

Energy Department

1 Introduction

The Nuclear Energy Act requires that licence-holders whose actions lead to the creation of nuclear waste have to manage the waste they produce. Those responsible for nuclear waste management assume responsibility for the planning, implementation and costs of the waste. The planning of nuclear waste management mainly means research and development done for the purpose of nuclear waste management operations. Posiva Oy, jointly owned by Teollisuuden Voima Oyj and Fortum Power and Heat Oy, runs Finland's most extensive programme for nuclear waste management research and development. In addition, other organizations responsible for waste management conduct research and development work related to their activities.

In addition to the nuclear waste programmes of the companies responsible for nuclear waste management in Finland, the Ministry of Economic Affairs and Employment (MEAE) has the Finnish Research Programme on Nuclear Waste Management (KYT). The main goal of the research programme is to ensure that that there is enough comprehensive expertise in the area of nuclear waste management as well as other readiness available for the use of authorities when evaluating different implementation methods and processes. In addition, the goal of the research programme is to support and complement the research programmes of the waste management organizations, and to further develop communication between the actors around this industry. The programme does not include research that is directly related to monitoring of the use of nuclear energy, licence management or the preparation of licence application materials. The steering group of the research programme may adjust the focus of the research each year. As described herein, the objectives and contents of the KYT2022 programme are based on the views of the working group appointed by the ministry.

1.1 Operating Environment of Nuclear Waste Management

Both in Finland and abroad, the operating environment of nuclear waste management will change considerably during the research programme period 2019–2022.

National operating environment

Several decision-making processes conducted by the authorities or the responsible waste management organizations during this programme period are directly or indirectly related to nuclear waste management procedures or timetables.

In November 2015, the government granted a construction licence for an encapsulation plant and nuclear waste final disposal facility. After the decision, Posiva started the construction of the final disposal facility in December 2016. Besides construction the work of Posiva will continue during the programme period as research, development and technical planning of the KBS-3 final disposal system. The research also continues in multiple topics supporting safety case. The main objective of the technical development and planning, however, is to move from the planning of the final disposal system towards demonstrating its technical performance in ONKALO. In addition, Posiva will continue its research and development activities with the aim of submitting the operating licence application for the encapsulation plant and the final disposal site at the beginning of 2020. The start of the operation of the encapsulation plant and the final disposal facilities would then be after the KYT2022 programme period.

The nuclear power plant unit Olkiluoto 3 will start its operation during the programme period after it has received an operating licence granted by the government. The Olkiluoto 1 and 2 nuclear power plant units will also continue their operation after the Government has granted new operating licences to run until the end of 2038. Under its licence, the Olkiluoto 3 (OL3) plant unit will be attached as part of the nuclear waste management system of the nuclear power plants already situated on Olkiluoto Island. This means that the interim storage and the final disposal site of the power plant waste (VLJ cave) situated at the plant site can also be used for the handling, interim storage and final disposal of

commissioning and maintenance waste of OL3. The expansion of the VLJ cave may become topical in the 2030s at the earliest.

The Hanhikivi 1 nuclear power plant is expected to enter the construction stage during this KYT programme period. In addition to the nuclear power plant unit, the facilities being built consist of nuclear installations which are used for the storage of fresh nuclear fuel, interim storage of spent nuclear fuel and for the handling and storage of low and intermediate nuclear waste. Fennovoima is applying for a construction licence for power plant waste independently. In connection with the final disposal of spent nuclear fuel Fennovoima is expected to continue negotiations about extended nuclear waste management cooperation with those responsible for nuclear waste management and to go ahead with its own final disposal planning and development as an alternative option.

The nuclear power plant units of Fortum Power and Heat Oy are licensed until the late 2020s. In the coming years Fortum is expected to tell more about its plans to continue the use of the power plants or to move on to the planning period of final disposal. The operating licence for the final disposal facility of the nuclear power plant and decommissioning waste in Loviisa is valid until the end of 2055, but the enlargement of the facility may become topical in the 2020s at the earliest. Licensing for enlargement would need to be done in good time before the actual technical extension.

The FiR 1 research reactor at VTT was shut down permanently in 2015. Since the shutdown the research and development work related to the research reactor has focused on the planning and execution of decommissioning. VTT applied for an operating licence in 2017 from the Government for the decommissioning of the research facility. During the research programme, VTT is expected to move on to the execution phase of the decommissioning, after the Government has granted the licence and other prerequisites related to the start of execution have been fulfilled. In addition, preparation of the decommissioning of the material research facilities at Otakaari 3 have been started at VTT.

The Nuclear Energy Act was amended in 2017 so that from the start of 2018 nuclear facilities need to apply for a decommissioning licence before demolition of any facilities. With the amendment, the licensing for the nuclear facility after any

decision in principle procedure has become a three-stage process. However, the decommissioning of VTT's research reactor is intended to be implemented on the basis of an operating licence referred to in the Nuclear Energy Act, because VTT applied for a licence for decommissioning of the research reactor before the change in the law became effective.

VTT started the building project at the VTT Centre of Nuclear Safety at the beginning of 2014. The building was finished in 2016. The Centre of Nuclear Safety includes modern experimental research facilities with hot cells, which can be used to study activated reactor materials but not spent fuel. In addition, laboratories for nuclear waste research and new radiochemistry and dosimetry laboratories were built there. The procurement and installation of key equipment for the Centre of Nuclear Safety is partly unfinished. In 2017, the Ministry of Economic Affairs and Employment set up a working group to consider nuclear waste management issues. Based on its work, the working group will issue an opinion in 2019 about the target state of the nuclear and other radioactive waste management and recommendations for reaching these targets. The recommendations cover e.g. the architecture of the nuclear waste management licences and other legislation related to nuclear waste management, open questions of nuclear waste management, final disposal options of highly active sealed sources, the challenges of the waste released from monitoring, securing the know-how, international cooperation, the national nuclear waste management programme (Nuclear Energy Act. section 27b) and the national programme of radioactive waste management (Radiation Act, section 87). The authorities, universities and licence-holders are represented in the working group.

Finland is reporting about nuclear waste and other radioactive waste management accords with international legislation. The national programme, which covers the aforementioned national nuclear waste management programme and radioactive waste management programme, was first prepared for the Commission in 2015 (MEAE 2015). The Finnish nuclear waste management programme and other radioactive waste management have also been discussed in the sixth national report delivered to the IAEA (STUK 2017).

International operating environment

International developments in nuclear waste management are expected to be active during the programme period. For example, the EU nuclear waste directive has already significantly influenced the practices and plans of the industry in the member countries. In Sweden, they are finishing off the processing of a licence application regarding the building and implementation of spent nuclear fuel encapsulations and final disposal facilities submitted to the authorities in March 2011. The Swedish nuclear safety authority SSM (Strålsäkerhetsmyndigheten) gave its own statement in January 2018; on the same day (23.1.2018) Nacka Mark- och miljödomstolen also gave a statement. Next they are waiting for the decision of the government. In France, the pre-review of the final disposal of highly radioactive waste was submitted in 2016 and the authority ASN (Autorité de Sûreté Nucléaire) has made an evaluation. In the USA, the Office of Spent Fuel and Waste Disposition (SFWD) of the Department of Energy (DOE) is executing its research programme about long-term storage, transport and a geological final disposal area. The decommissioning of nuclear plants is also a significant area of focus because of the USA's old nuclear programme. The importance of decommissioning is estimated to grow worldwide because of the many reactors which are already closed.

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

European Union (EU) funding has been implemented as framework programmes through the research and education programmes of EURATOM. At the moment the Horizon 2020 programme for 2014–2020 is continuing and its nuclear waste management application calls were in 2014 and 2016. In 2009, the technological forum IGD-TP (Implementing Geological Disposal - Technology Platform) was founded. Its role is to coordinate the nuclear waste management research done in the sphere of EURATOM. The participants from Finland in the IGD-TP are Posiva and some other organizations from the nuclear waste management field. The SNE TP-Nugenia research programme includes research-related dismantlement of the plants and plant waste processing, which complements the objectives of the IGD-TP in the field of waste management. In 2018, VTT joined the SITEX_Network

(continuation of the SITEX-projects, Sustainable Network for Independent Technical Expertise of Radioactive Waste Disposal), which is developing nuclear waste management expertise in the area of the EU, independently of licence applicants.

Nuclear waste research funded by the EU will in the future be done in the European Joint Programme (EJP). The funding of the programme is based on the so-called co-funding principle, i.e. 50% of the funding must come from the EU member countries. The first EJP call opens in September 2018; the research topics were selected based on a wide international enquiry. An organization participating in the EJP may be placed under one of the following organizational categories: nuclear waste management, technical support or research. Finland has three organizations participating in the EJP administration: Posiva Oy (nuclear waste management organization), VTT (technical support organization) and the University of Helsinki (HY, research institute). Other interested domestic organizations may participate through a cooperation agreement with one of the aforementioned organizations. The MEAE is the programme owner in Finland. A national support group, in which the KYT research programme is also represented, is supporting Finnish participation in the EU research programmes.

Each organization can apply for funding from the EJP and KYT2022 research programmes with research applications that support and supplement each other. Finnish nuclear waste management research can benefit significantly from the research done in the EJP research programme, although this requires that the results of EJP research projects are also publicized by the KYT2022 research community.

The Radioactive Waste Management Committee (RWMC) of the Nuclear Energy Agency (NEA), which is part of Organization for Economic Co-operation and Development (OECD), has working groups that deal especially with long-term waste and spent nuclear waste management, the long-term safety of final disposal and the decommissioning of nuclear facilities. The RWMC has three working groups altogether. The Forum on Stakeholder Confidence (FSC) focuses on the societal acceptability of nuclear waste management. The Integration Group for the Safety Case (IGSC) focuses on the safety of final disposal from different viewpoints and developing the safety case of final disposal. The Working Party on Decommissioning and Dismantling (WPDD) focuses on the strategies and dismantling techniques,

decommissioning waste, funding and costs of decommissioning. The RWMC convenes once a year. The working groups organize seminars, workshops and annual meetings yearly, and publish reviews and brochures. The RWMC and its working groups also include representatives from Finland. In practice, the RWMC also has representation from the KYT programme.

The NEA is founding a new committee on the topic of decommissioning: the Committee on Decommissioning of Nuclear Installations and Legacy Management (CDLM). The new committee is expected to start its activities in 2019. At the same time, the topics concerning decommissioning will be transferred from the RWMC to the aforementioned decommissioning committee. Finland will also participate in the activities of the decommissioning committee.

The Finnish nuclear waste management actors participate actively in the preparation of international recommendations and European safety standards. STUK is working to influence the standards of the International Atomic Energy Agency (IAEA) concerning nuclear waste management, especially through the Waste Safety Standards Committee (WASSC). Specifically STUK is participating in preparation of standards and guidelines and by working on IAEA projects (e.g. International Intercomparison and Harmonisation Project on Demonstrating the Safety of Geological Disposal, GEOSAF). In addition to guideline work, STUK is acting as a Finnish contact organization in the information exchange systems of the nuclear energy industry maintained by the IAEA (e.g. IAEA Online Information Resource for Radioactive Waste Management, NEWMDB). As members of the IAEA evaluation group, the experts at STUK also participate in peer reviews of other member countries. IAEA cooperation allows an overview of nuclear waste management matters, even where these are not directly related to research. STUK also participates in the work of the Working Group on Waste and Decommissioning (WGWD), which is part of WENRA (Western European Nuclear Regulators Association). The object of the WGWD is to harmonize the standard of authorities concerning nuclear waste and decommissioning. The licence-holders Fortum and TVO are involved in commenting on and following the standard and guideline work of WENRA, the IAEA and the European Commission through the European Nuclear Installations Safety Standards Initiative (ENISS) group.

The NKS (Nordic Nuclear Safety Research) is a Scandinavian co-operation network funded by ministries and power companies. The NKS supports the organizing of seminars and research on nuclear safety, radiation safety and standby activities. Within the limits of the NKS, three decommissioning seminars have been organized and studies made about e.g. measuring hardly detectable radionuclides in decommissioning waste. The first seminar took place at Risø in Denmark in 2005, the second seminar was at Studsvik at Sweden in 2010 and the third at Halden in Norway at the end of 2013. The NKS has planned a decommissioning workshop to be held in Risø at the end of 2018.

1.2 Previous Public Research on Nuclear Waste Management

Publicly financed nuclear waste management research was launched in Finland in the early 1970s, on the initiative of the Atomic Energy Advisory Board. Public coordinated research programmes on nuclear waste management have been conducted since 1989 (see Table 1).

Table 1. Public administration research programmes.

Period	Research programme
1989–1993	Publicly financed nuclear waste management research programme JYT (Vuori 1990, 1991, 1993)
1994–1996	Publicly administrated nuclear waste management research programme JYT2 (Vuori 1997)
1997–2001	Public sector´s research programme on nuclear waste management JYT2001 (Vuori 2000, Rasilainen 2002)
2002–2005	Finnish Research Programme on Nuclear Waste Management KYT (Rasilainen 2006)
2006–2010	Finnish Research Programme on Nuclear Waste Management KYT2010 (KYT-johtoryhmä 2005)
2011–2014	Finnish Research Programme on Nuclear Waste Management KYT2014 (TEM 2010, TEM 2016)
2015–2018	Finnish Research Programme on Nuclear Waste Management KYT2018 (TEM 2014)

International evaluations of the KYT research programme have been conducted in 2007, 2012 and 2017 (Apted & al. 2008, 2013, TEM 2017). The proposals of the evaluation groups have already been taken into account during the research programmes and separately at the planning phase of every research programme.

In the latest evaluation, it was noted that the administration of the research programme is being performed efficiently and the programme has extensive and profound expertise on nuclear waste management. The continuation of the research programme was seen as expedient.

- The evaluation group listed separately four significant challenges and 10 proposals (MEAE 2017); the challenges were as follows:
  - the lack of synergy between international waste organizations and waste programmes (e.g. EJP, SITEX);
  - ensuring the balanced development of national know-how in nuclear waste management so that it is possible to guarantee an independent level of expertise to support the authorities;
  - a stronger role for the steering group to ensure the visibility and project quality of the programme;
  - the importance of VTT's Centre for Nuclear Safety as a national infrastructure investment and its utilization in the KYT programme.
- The proposals have included:
  - the international visibility of the KYT programme should be significantly improved;
  - a stronger role for STUK in guiding the content of the research;
  - a stronger coupling to nuclear energy industry actors to better identify the topics which need research, and to support development of the right competence;
  - the possibility to expand the topic of the research programme Naturally Occurring Radioactive Material (NORM) to cover waste and the safety of geological disposal during use.

1.3 Overall Safety in Nuclear Waste Management

Overall safety in the planning and management of the treatment, storage and disposal of nuclear waste forms a wide-ranging and interdisciplinary research entity that requires good collaboration between research organizations and nuclear waste management actors. The most important part of overall safety is the architecture of the disposal concept, but overall safety also covers functional processes and operational safety at all stages in the life cycle of nuclear waste management facilities (e.g. disposal and encapsulation facility).

Components of overall safety

In addition to the disposal facility and its technical systems and release barriers, it is important to understand the collaboration and interactions between organizations as factors affecting overall safety (from this point of view, overall safety is all about the "organization of organizations"). This kind of comprehensive understanding of safety requires that the related research is also comprehensive and interdisciplinary. Combining different disciplines provides tools to manage the complexity of the safety of nuclear waste disposal and thus it may improve the overall level of safety.

Safety and risks are traditionally discussed in isolation within regimes or disciplines/paradigms (e.g. safety in road traffic or air traffic) and the discussion may be hampered by a lack of relevant analogous references. This is also the case with nuclear waste management and radiation safety, which in extreme cases may lead to the acceptance of relatively large risks or to extremely strict safety criteria. Reducing risks to people is evidently not always as effective as intended in the aforementioned extreme cases. Defining an acceptable safety level is, however, quite complicated as it depends on people's conception of risks and the acceptability of different risks.

The main research topics and related interfaces linked to overall safety are described in Table 2.

Table 2. Research topics related to overall safety and the relevant research questions related to Defence in Depth (DID).

Research topics	Main research object Research questions related to defence lines in Defence In Depth (DID) system
The conception of overall safety	What are the defence lines in the planning of facility and how should they be formed? How do defence lines appear in the behaviour of an organization network ("organization of organizations")?
Functional processes (Systems Engineering)	How are defence lines built in planning processes? Are defence lines visible in the planning of operations?
Facility and factors affecting the safety concepts	Structural defence lines Functional defence lines How do the know-how of an individual and a single organization show in the defence lines of a facility?
Risks and risk acceptability	What is an acceptable safety level and how does it relate to common risk perception and risk acceptance?

Overall safety topics related to nuclear power plants have been studied in the SAFIR programme, focusing on a nuclear power plant system, its environment and system architecture. Overall safety related to nuclear waste management therefore has a substance interface with SAFIR programme.

Objectives

A characteristic feature in the overall safety of nuclear waste management (e.g. handling, storage and disposal) is that both operational and long-term safety must be considered. Central research topics are issues that are located on interfaces between subsystems or engineering disciplines, or issues that dominate when managing the whole system, e.g. design basis, coupling design basis to long-term safety, and the behaviour of individuals and organizations. Disposing of nuclear waste for the first time ever (Finland will be the first country to carry out spent nuclear fuel disposal) in an evolving technical environment will bring new challenges for nuclear safety. New technical systems will require new methods to assess the behaviour and safety of the new systems.

Management of the safe use of a nuclear waste facility requires that the related organizations preserve and develop their facility experience and know-how over decades. Systematic transfer of knowledge and know-how to new generations of experts is central to overall safety. Ensuring operational and long-term safety of a nuclear waste facility requires technical solutions based on the planning of processes and the safety architecture (disposal concept). It also requires people and organizations that are ultimately responsible for all activity. Activities affecting safety include: defining safety requirements; planning, manufacturing and installing the necessary technical solutions; evaluating these solutions' compliance with requirements; operation and control of the solutions; and ensuring the proper operating preconditions. Preparation at different levels for operational disturbances and accidents as well as for long-term evolution schemes and rare events concerning the facility is a central starting point in safety thinking.

Because the service life of a disposal facility is typically very long, ensuring safety is a continuous process that needs to be adapted to possible changes in the operating environment. Ensuring safety includes also preparing for very rare evolution schemes that naturally are linked to considerable uncertainties. Uncertainties are managed with the help of safety cases, and other estimates based on probabilistic and deterministic analyses of results of different evolution schemes. Comprehensive safety planning also includes risk considerations and safety margins that are used to manage uncertainties.

The objective of the work done in this research area is to increase understanding and control of factors relevant to overall safety across the life cycle of a nuclear waste disposal facility, and to increase consideration of overall safety features in individual research projects. To help reach this objective it is necessary to understand the importance and mutual interaction of relevant factors and to evaluate and develop the know-how and the impact of the modus operandi of nuclear waste management actors. Improving communication on nuclear waste management safety matters within the nuclear waste management community and between that community and other safety critical industries is central when spreading knowledge about safety solutions and their acceptability. Research projects should produce new knowledge but also support the application of the knowledge in nuclear waste management organizations as part of developing overall safety.

2 Organization of the Research Programme

2.1 Purpose and Objectives

The purpose of the KYT2022 research programme is based on the provisions of the Nuclear Energy Act (990/1987). The Act states that those responsible for nuclear waste management are required to participate in funding such research activities, research infrastructure and additional training that aims to ensure that *"the authorities have such sufficient and comprehensive nuclear engineering expertise and other facilities at their disposal that are needed for comparisons of the various ways and methods of carrying out nuclear waste management"* (section 53b, as provided by amendment act 676/2015). The annual KYT programme payments applicable to those responsible for nuclear waste management depend on the amount of liability set for each actor based on the Nuclear Energy Act. The contents of the research programme consist of nationally important research areas.

The KYT2022 research programme supports training and education in national nuclear waste management and ensures the essential national expertise is continuously available. The programme also promotes scientific and high-level expertise and general understanding of the nuclear waste management field. The research programme emphasizes education as one of the evaluation criteria for funded projects. The research programme can offer partial funding for thesis work if the contents fulfil the objectives set in this framework programme. The research programme can also fund updating education on nuclear waste management that effectively helps those entering expert positions in nuclear waste management. It is predicted that the need for nuclear waste management experts will grow in the period from 2017 to 2030 (TEM 2012, Hämäläinen & Suolanen 2017).

The KYT2018 research programme serves as a discussion and communication forum between authorities, organizations engaged in nuclear waste management and research organizations. The aim of this forum is to facilitate efficient utilisation of limited research resources while striving to ensure sufficiently versatile and interdisciplinary research teams for individual research projects and experienced support groups for the research projects. Efficient information exchange can also help in avoiding research overlaps, and in coordinating participation in international projects, for instance. The programme also collaborates with the SAFIR2022 research programme. The objectives of KYT2022 are discussed in more detail in Chapter 3.

According to the Nuclear Energy Act, those responsible for nuclear waste management must assume responsibility for the planning, implementation and costs (including those related to research and development, of managing any waste they produce). Projects falling within the direct responsibility of nuclear waste producers are therefore excluded from the KYT programme. In addition, research conducted in direct support of STUK's supervisory duties is also excluded. However, different actors can offer e.g. their equipment and experimental research data for researchers in the KYT programme to use, in which case the equipment and data will be more widely utilised e.g. in theses. The research in KYT can be dependent on the concept used or the location selected if the research need requires this. The research topics must benefit the regulator and licensees. Different actors can also offer their research equipment and experimental data for the KYT programme and researchers to use so that the equipment and material can be more widely used.

The KYT20222 research programme supports and encourages participation in international nuclear waste research, for example in the EJP. Foreign experts' participation in the KYT programme is possible in a joint project with a Finnish research group, so that the project can better improve Finnish nuclear waste management expertise.

2.2 Administration of the Research Programme

Research programme activities are based on mutual co-operation and the distribution of responsibilities between the Ministry of Economic Affairs and

Employment (MEAE), the programme steering group, one or several support groups, the coordinator, and research projects. The division of responsibilities between research programme actors is presented briefly below. Details of the administrative practices related to the programme are available in the operating instructions posted on the research programme website (http://kyt2022.vtt.fi/).

Steering group

The research programme is governed by the steering group whose chairman is from the Radiation and Nuclear Safety Authority (STUK). The steering group includes representatives from the MEAE, STUK, the Ministry of Social Affairs and Health, the Ministry of the Environment, Fortum Power and Heat Oy, Posiva Oy and Teollisuuden Voima Oyj and Fennovoima Oy as an expert member. The secretary is the research programme director from VTT Technical Research Centre of Finland. The steering group can add experts on a temporary or permanent basis.

The steering group is responsible for the research programme's strategic guidelines. Complementing the general guidelines in the framework programme, the group can propose annual focus areas of research to the MEAE, in the project call or in separate instructions by the steering group. The steering group evaluates submitted project proposals and gives the annual financing recommendation for projects that it considers best fulfil the needs described in the framework programme and the annual focus areas.

Support groups

The steering group appoints the necessary number of support groups. These act as technical specialist bodies in support of the steering group, which appoints their chairpersons and members. Support groups are responsible for annually evaluating the proposed research projects, and for the follow up and guiding of projects receiving funding. Deep scientific expertise is required for guiding the research projects, and the KYT2022 steering group tries to ensure the necessary resources within the limits of its jurisdiction. The steering groups for KUT2022 and SAFIR2022 can also agree on evaluation and support responsibilities crossing the research programme boundaries.

Additionally, ad hoc working groups can be nominated if necessary.

Director and assisting project expert

The research programme director is responsible for programme administration. The director is selected on the basis of the competitive bidding process set out in the Act on Public Procurement and Concession Contracts (1397/2016). The KYT2022 director is from VTT. The selection criteria are: experience in the nuclear waste management area, project management experience, knowledge of national and international research programmes and a suitable degree in higher education. In addition, it is required that the director's home organization provides support for the coordinator, e.g. in IT and financial administration and in human resources. The director is assisted by a project expert, who will have a degree in higher education and experience in the nuclear waste management field, in their home organization.

Website

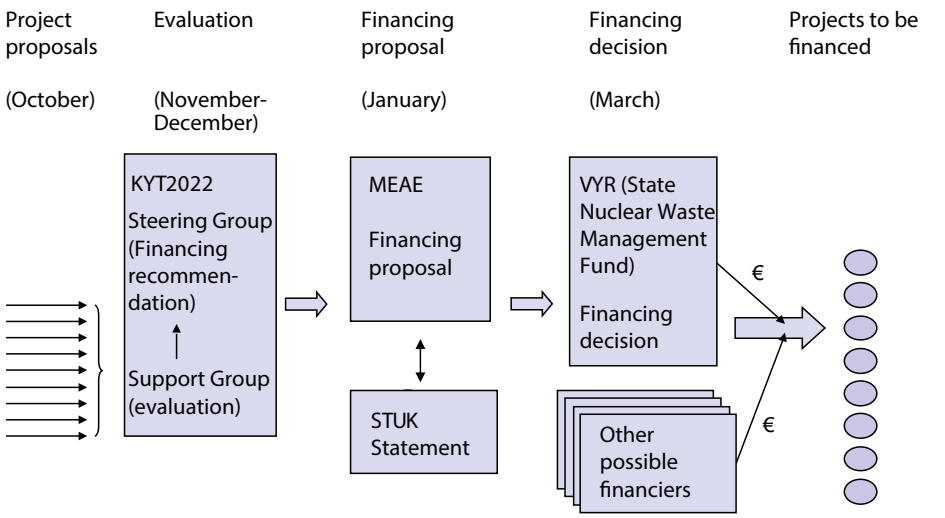
The research programme communication is mainly done through the research programme website (http://kyt2022.vtt.fi/)[1]. The research programme and project reports as well as the documents on the call for proposals are published on the site. The website also has information on the research programme seminars and steering group decisions. The website also has an English version.

2.3 Project Call and Financing Decision

Participants in the KYT programme are selected via a public project call process, Figure 1. The opening of the call is announced in a letter of invitation from the MEAE. The letter of invitation is also available on the webpage of the KYT2022 programme (http://kyt2022.vtt.fi/). Funding can be applied for the project duration from one to up to four years.

1 The first call is made using the KYT2018 website.

Figure 1. Decision-making on research projects under the KYT2022 programme. The other potential financiers are usually research institutions that channel their own financing into their projects. Often the research organization also allocates its own funding to the research.



The steering group evaluates research project proposals entered by the due date given in the application process. The support groups function as technical expert bodies and evaluate the applications. The steering group prepares a financing recommendation to the MEAE. Based on the evaluation of the supporting groups, the steering group writes a feedback report on the content of the project proposal. The party submitting a project proposal will be informed of the financing recommendation and the feedback report.

The MEAE submits an official financing proposal about the annual research project entity to the State Nuclear Waste Management Fund based on the financing recommendation. Before submitting the financing proposal, the MEAE requests that STUK issue a statement (Figure 1). The State Nuclear Waste Management Fund finances KYT2022 projects on an annual basis based on the MEAE financing recommendation. The Fund grants funding to KYT projects for one year at a time.

The steering group can recommend funding for one or more years at a time. If the research group applies for two or more years of funding, the application must cover

the entire research period. Additionally, the research group must send a notice of continuation to MEAE each year after the original application. If significant changes occur or the research project needs more funding than previously estimated, the research group must make a complete new application so that the project can be re-evaluated as a whole. Otherwise, the research project funding will continue based on yearly progress and the funds available in the research programme. If the project is lacking progress, the steering group can propose a reduction in the budget or discontinuation of the project. The funding distributed annually is based on the provisions of the Nuclear Energy Act, which defines the amounts that those responsible for nuclear waste management are required to pay into the State Nuclear Waste Management Fund. During the research period 2019–2022, the annual research funding is estimated to be between 2.8 and 3.3 million euros, depending on the year.

2.4 Project Types within the Research Programme

Projects proposed for the KYT programme may include individual research projects or larger coordinated research entities. Wider research proposals in the most relevant research topics should be integrated into coordinated projects. The research topics seen as most relevant for KYT2022 are discussed in Chapter 3.

In practice, the programme accepts two kinds of projects:

- Individual research projects, in which the project manager is responsible for project implementation and contacts with the research programme
- Coordinated projects, where the project coordinator is responsible for building a research team and preparing a project proposal. The project coordinator is also responsible for the internal coordination and administration of the project, e.g. the project plan and reporting.

A coordinated project is a project type introduced in the previous KYT programmes. The aim of coordinated projects is to integrate wider research proposals in the

most relevant research topics. Several research institutions participate in a typical coordinated project, which may cover the entire KYT2022 research period. In essence, a coordinated project is a small-scale research programme, where the project coordinator is responsible for building a research team and for preparing a project proposal. The details on running a coordinated project are described in the KYT2022 code of conduct.

The steering group will for its part ensure that the financial recommendation includes projects of different duration and type. The support groups evaluating the proposals can request changes through the steering group. Recommendations can be made for applications to be merged or they can be funded only partially. Performing the required changes and submitting updated applications is a requirement for receiving funding from the State Nuclear Waste Management Fund. If the research project duration is extended for longer than the original plan, e.g. additional research needs are discovered during the project, the project can make a new application in the next call. The State Nuclear Waste Management Fund grants financing for KYT projects one year at a time (see Figure 1). In the case of projects lasting several years, the steering group strives to ensure project continuity, provided that the project progresses according to plan. If the project fails to do so, the steering group may propose that financing be cut or interrupted.

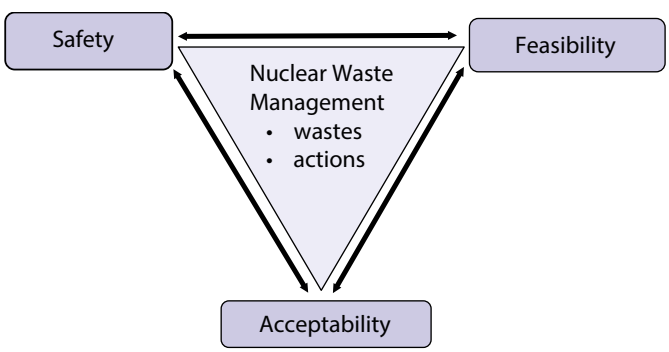
Under the KYT2022 programme it is also possible for the steering group to start small projects outside of the public call. These can be for example projects on topics that did not receive any applications in the call or project proposals submitted in the call that do not yet fulfil the requirements for funding. In the latter example the money is to be used by the research group in such a manner that their project idea can receive funding in the next call. The steering group can also fund other types of projects if they are expected to bring significant benefits to nuclear waste management research.

3 Detailed Objectives of the Research Programme

The research topics in KYT2022 are a continuation for the previous KYT2018 programme. Additionally, the results of the international evaluation have been followed where applicable. The most important criteria for selection is, however, the research needs expressed by the Finnish nuclear waste management authorities and other actors.

Research within KYT2022 is divided into topics interacting with each other: (1) safety in nuclear waste management, (2) feasibility of nuclear waste management, and (3) acceptability of nuclear waste management (Figure 2). When evaluating safety, the discussion on acceptability must be taken into consideration as well as the boundary conditions arising from technical feasibility. When evaluating feasibility, the starting point is a safe solution and its public acceptance. Public acceptance is dependent on the safety and feasibility. The research programme steering group can specify the emphases between and within topics on an annual basis.

Figure 2. Main research topics of the KYT2022 research programme.



Nuclear waste is defined as the radioactive waste created in or as a consequence of nuclear energy production. Nuclear waste management comprises of all the actions regarding safe handling of the waste, such as characterization, separation, packaging, transportation, interim storage and final deposition. The Finnish nuclear waste management is based on deep geological deposition, meaning the nuclear waste is deposited in space excavated in bedrock. Depending on the characteristics of the waste, e.g. half-life and activity, the repository depth alternates between hundred metres (low and intermediate waste) and 400 metres (high-level waste), approximately. Surface repositories are also investigated for very low-level waste.

Structures are built to slow radionuclide migration around the nuclear waste, e.g. waste packages, buffer materials, fill materials, closure. Together with the natural barrier (bedrock), these form the multiple barrier system used in nuclear waste management. In the case of a radionuclide release, the multiple barrier system is to slow the radionuclide so that upon entry to the human environment they will not cause significant exposure. A large part of nuclear waste management research focuses on the multiple barrier system and the effect its possible failures have on the long-term safety of the repository. Research topics regarding safety of final deposition are listed in Table 3.

Table 3. Research topics in nuclear waste management for different waste categories. The different waste types are at different phases of the waste life cycle in Finland. Spent nuclear fuel repository licensing is underway; power plant waste is a licenced routine activity; and decommissioning waste deposition is currently being prepared.

	Waste category		
Research topics	Spent nuclear fuel	Power plant waste	Decommissioning waste
Overall safety	x	x	x
Characterization	x	x	x
Sorting		x	x
Packaging	x	x	x
Transportation	x		
Interim storage	x		
Final deposition	x	x	x
- Performance analysis	x	x	x
- Waste product	x	x	x
- Microbiology	x	x	x
- Waste package	x	x	x
- Buffer material	x		
- Closure	x	x	x
- Bedrock	x	x	x
- Biosphere	x	x	x

The main research areas and their possible research needs are discussed in more detail in the following sections.

3.1 Safety of Nuclear Waste Management

Safety is the most significant requirement in the planning and execution of nuclear waste management. It is also an interdisciplinary topic that is challenging to supervise. In order to ensure long-term safety the regulatory authorities must have high-level expertise on nuclear management safety available independent of the licensee and the regulator.

3.1.1 Basic Factors in Safety

Research needs

One research challenge is to form a uniform framework for assessing overall safety in the area of nuclear waste management. The framework will structure further the traditional defence in depth (DID) concept by integrating into the same system safety-maintaining structures, process systems, and activity of organizations and individuals with an eye on operational and long-term safety. In line with the DID concept, ensuring safety will take place on various consecutive, complementary operational levels. The DID approach could be described as safety thinking in depth. So far, different aspects of safety, based on different technological disciplines or traditions in nuclear safety, have been studied relatively separately. Individual safety objectives emerging from different traditions, although as such reasonable, may however contradict each other. This can cause problems in safety planning and verification of the planning. In addition, there is a danger that the planning becomes unbalanced if there is no uniform basis to value different aspects of safety. Forming a framework to assess overall safety is an identified research need in KYT2022.

There is a need for research about how to best integrate within a common framework:

- expected disturbances and accidents in a nuclear waste management facility;
- preparation for different evolution schemes and rare events in a disposal facility <-properties of disposal site and performance of engineering barriers;
- effect of man and organization on safety functions;
- requirements of nuclear security and safeguards -> 3S (safety, security, safeguards);
- roles, operating logics, tasks and impacts of nuclear waste management organizations on maintaining DID;
- risk perceptions and risk acceptability.

The target is a comprehensive model for DID that can be used as an objective basis for safety assessment and decisions in challenging evaluation cases. This is always important when there is a problem that is multidisciplinary and crosscutting and does not focus on the sector of any individual authority, or when there is an outside requirement or expectation concerning nuclear safety that differs considerably from earlier ones.

Overall safety understanding of a nuclear waste facility

Assessing safety must be done with objective criteria that are without subjective judgement by a planner, licence applicant or authority, even though reaching complete objectivity is a challenging goal. When assessing safety one must take into account a wide spectrum of different factors impairing safety or affecting the safety concept itself. Threats to overall safety must cover at least:

- failures in operation and accidents affecting operational safety;
- disturbances and initiating faults: different construction-induced disturbances in bedrock and initial faults in the engineering barriers;
- evolution scenarios in the disposal facility that impair long-term safety, natural and man-made
- incorrect action by man or organization;
- methodology of safety case: is the correct methodology used in the safety assessment?

In line with the DID concept there must be numerous independent levels of defence against different threats (e.g. disposal site selection, control of construction and manufacturing, monitoring, multibarrier principle, and preparation for different evolution schemes). In nuclear waste disposal, independent active radiation protection measures in line with the overall safety principle cannot be fully applied, and that is why long-term safety of nuclear waste disposal is largely based on a system of release barriers complementing each other with passive safety functions, in other words on a multibarrier system. Therefore, it is especially important to understand the interactions between the processes and barriers (subsystems) and the resulting properties of the whole disposal system, that is, to see a disposal

facility as a "system of systems". In addition, it must be possible to take into account risks related to actions by man and organizations, and to manage the risks thus induced at all stages of the facility's life cycle.

In order to be able to form a concept for overall safety for a nuclear waste facility vis-a-vis different risks and for preparing against these, it appears necessary to have a commensurable method of handling the risks. When scaling the facility and subsystems against different threats in operational and long-term safety, different margins for planning and safety assessment are traditionally used. However, handling margins in different technological disciplines are not uniform. The acceptance criteria used in deterministic analyses often include margins, so that exceeding the criteria by a small amount will not directly lead to considerable worsening of the consequences. A probabilistic analysis tries to handle different factors in a commensurable way, but its focus is limited to evolution schemes leading to damaged waste packages or releases to the environment. In addition, defining probabilities for evolution schemes over a long period of time includes considerable uncertainties. It is necessary to map the concept and application of safety margin in different technological disciplines and to create a method for uniformly comparing safety margins currently used in different ways. A clear understanding of safety margins would also better facilitate the use of a graded approach in practice.

Organization, man, stakeholder groups

Numerous organizations have an impact on the safety of a nuclear waste facility at different stages of safety case preparation, and in planning, construction, commissioning and use of the facility. One research need is to study the roles and operational practices of personnel, organizations and stakeholders as a prerequisite for overall safety. In order to take care of overall safety the organization must act in a responsible way. Responsible operation in an organization in regard to safety requires responsible safety management. Safety management will influence behaviour within the organization but also in guiding work chains and delivery chains and in organizing collaboration with different outside partners. It is necessary to identify factors in safety management that are critical to overall safety.

Functional processes supporting overall safety and planning management (systems engineering)

Functional processes linked to the planning, safety case, construction, and use of a nuclear waste facility have an effect on the overall safety of the facility. Overall safety is affected by the systems, structures and components of the facility and information concerning these, but also by functional processes linked for instance to management, planning, quality management and procurements.

In order to manage overall safety the field requires clear, jointly accepted and well-described functional processes, functional practices and information models. The structure of safety cases (i.e. information model) and functional processes needed to produce the information required must be studied and developed.

Factors affecting technical safety concepts

To ensure operational safety of a nuclear waste facility, facility planning must include preparations for different internal and external incidents that the facility must be able to survive even in the event of there being faults within the facility. In order to demonstrate this, fault and effect analyses are made as well as analyses concerning the behaviour of the facility as the consequence of the incident under study. In addition, the quality of planning is studied with probabilistic risk assessment (PRA).

Long-term safety of nuclear waste disposal is based on planning, construction and preparation during use that together result in an acceptable initial state of the system from a long-term safety point of view. From the long-term safety viewpoint facility planning will have to take into account evolution schemes considered probable as well as those considered rare. In order to demonstrate the safety of a disposal facility, it is necessary to define for release barriers complementary safety functions that form the basis of long-term safety. A safety case must show compliance with nuclear and radiation safety requirements on long-term safety, and the feasibility of the disposal concept, technical release barriers and disposal site. The safety case must discuss possible different evolution schemes in the disposal facility, including rare evolution schemes that could impair long-term safety. The safety case covers a mathematical safety assessment and complementary studies.

Integration of different levels in a DID concept nevertheless requires a comprehensive analysis which includes operational safety, construction and preparation during use, and long-term safety. It is necessary to develop methods that enable better understanding and further development of overall safety.

Risk perception and risk acceptability

The fundamental principle in using nuclear energy is that it must be safe and must not cause damage or harm to people, the environment or property. The safety requirement covers the entire life cycle of nuclear energy, including nuclear waste disposal and its long-term safety.

The principle in nuclear waste disposal is that the radiation safety criteria applying to future individuals and populations are the same as those that currently apply. The radiation dose criterion applied for nuclear waste disposal is very low compared to the average radiation dose every inhabitant of Finland receives in any case.

Further principles in nuclear waste disposal are to isolate nuclear waste as long as possible from the human environment and to reduce the risk of human intrusion into the disposal facility. The deeper the disposal, the better the waste is isolated from possible disturbances at ground surface and the longer the transport route to the human environment if the isolation would fail; deep disposal will also reduce the risk for inadvertent human intrusion as compared to close to surface disposal or interim storage. Engineering release barriers act in the same way. Long-term safety of nuclear waste disposal is based on complementary release barriers, in other words on a multibarrier principle, in which the possible failure of one release barrier shall not compromise the safety of disposal. Release barriers include natural barrier (bedrock) and engineering barriers (e.g. spent fuel disposal canister, bentonite buffer, tunnel backfill, and tunnel plugs and other closure structures).

Possible dose rates in the future are estimated in a safety assessment using analyses based on different scenarios (possible alternative evolution schemes of the disposal system). The analyses often apply conservative assumptions: using assumptions that overestimate the consequences the aim is to compensate for uncertainties related to future evolution schemes.

When assessing the safety of nuclear waste disposal over long periods of time, safety must be considered as a whole, which includes the performance of release barriers in the disposal system, transport of released radionuclides, and dose rates in different evolution schemes. Assessing safety in the future will include unavoidable uncertainties - the future cannot be predicted. It is only possible to use the best available knowledge to estimate safety-relevant evolution schemes in advance and to plan systems that cope with different threats as well as possible. In safety assessment it is important to understand related uncertainties and, based on this, create an understanding of risks. When making decisions concerning the safety and acceptability of nuclear waste disposal, the risks must be on acceptable level. It is necessary to study what kinds of risk perception, risk management and risk acceptability are applied in other fields as reference for those in nuclear waste management.

3.1.2 Spent Fuel Management

The most significant research challenges in nuclear waste management are related to long-term safety. The safety case of the final disposal of spent nuclear fuel will be written by Posiva. The possible research topics for the KYT2022 programme are related to the performance assessment of the final disposal system and the performance of its components, on which the safety case mainly rests.

The multibarrier system of the underground final repository consists of technical and natural barriers. Starting from the spent nuclear fuel, the surrounding multibarrier system includes the capsule, bentonite barrier, the tunnel filling material and the bedrock, through which the radionuclides are likely to move after their release, mainly carried by groundwater. The exposure of people and other organic nature to radionuclides would take place in the biosphere.

Performance assessment

In the KYT2022 programme there is no target for formulating the overall safety case, which is the responsibility of the licence-holders. Instead, a limited performance analysis can be made of the essential interaction phenomena of the multibarrier system affecting long-term safety. Possible research topics include:

- testing the fundamental hypotheses used in the reported safety case;
- interdisciplinary research on the transient phase[2] phenomena after the closure of the final disposal facility. In addition, the safety impact of these phenomena and the uncertainties related to assessment of these safety impacts;
- research on the most important sub-systems for the safety of the final disposal facility.

The safety case has some central hypotheses whose scientific testing for long-term safety fits well with the goals of the KYT programme. Examples are study of the properties of the spent fuel in final repository conditions, the hypotheses of the paleohydrogeological evolution affecting long-term safety, and how the hypotheses are made concerning radium behaviour affecting long-term safety (e.g. release rate, transfer velocity, coprecipitation). Other central hypotheses may also be tested.

After closure of the final disposal facility, there will be simultaneously multiple kinds of ambient and internal transient phase phenomena: chemical, rock mechanical, hydrological, thermal, biological and radiation related. Multiple coupled processes are also related to these. The most intense transient phase will be over in few thousand years, when the heat generation has significantly decreased, but it could cause partly irreversible changes to the multibarrier system. Detailed research of the transient phase and its effect mechanisms (the phenomena and their mutual interactions taking place in the final repository) requires simultaneous well-coordinated interdisciplinary analyses of many fields. After the interdisciplinary analyses, the safety effects of the transient phase can be estimated.

Final disposal safety analyses have shown that C-14, the radioactive isotope of carbon, is a significant radionuclide in operating waste, spent fuel and decommissioning waste. There are still uncertainties about its speciation, i.e. the chemical form in which C-14 appears. These are correspondingly reflected as

2 After closure, many properties of the final repository will change rapidly and simultaneously over time and space. This highly complicated phase is here called the transient phase.

conservative assumptions in safety assessments regarding its chemical behaviour. Studying the behaviour of C-14 in greater detail is therefore justified.

Since Finland is moving towards industrial scale final disposal, it should be noted that the changes in the industrial process of the technical barrier system even at sub-system level require safety assessment of the possible effects. Industrialization is discussed in more detail in section 3.2.

In addition to the technical aspects noted above, the aim in the research programme is to couple the technical performance/safety case approach with the acceptability viewpoint. Demonstrating the technical performance and safety itself is not enough. It is also necessary to gain societal acceptability for the final disposal project to advance.

Sub-systems

The following paragraphs describe the phenomena and sub-systems concerning spent fuel deposition as well as the related research needs. Some of these are also relevant to power plant and decommissioning waste described later in the section. Research topics on concrete are also relevant for low and intermediate level waste repositories and biosphere research is needed for intermediate, low and very low level waste repositories. One of the objectives in the KYT2022 programme is to study the interaction of subsystems in the repository, because for long-term safety evaluation the multibarrier system must be reviewed as a whole.

Spent fuel

Spent fuel is the most active type of nuclear waste and its nuclides are long lived, so its characteristics are especially important to know. Finnish nuclear power plants have been able to licence for higher acceptable fuel burn up due to fuel development, experimental fuel research and experience in fuel use. Different burn ups cause different nuclide inventories in different spent fuel batches, which has to be taken into account in nuclear waste management and especially in long-term

safety evaluation. Different fuel cycles and the proliferation risk[3] related to them are essential global topics when considering alternatives to direct deposition. A possible new fuel cycle is related to the small modular reactors (SMR) which are being planned in several countries and are attracting international interest. It is possible to collaborate with the SAFIR2022 programme on fuel cycle topics.

Capsule

The capsule can be viewed as the single most important release barrier in the KBS-3 concept. The authorities must have sufficient levels of high-level information on the performance of the capsule and the main phenomena affecting it as well as the methods used in performance assessment. The principles, assumptions and limitations of the evaluation have to be known. Even though the performance of the capsule has been studied for a long time, there is still discussion on the topic and additional verification is needed on e.g. copper corrosion in general and stress corrosion mechanisms. Creep studies on copper using non-destructive evaluation, copper deformation mechanisms, cast iron characteristics and copper stress corrosion are examples of possible research topics.

Buffer and filling materials

The performance assessment of the KBS-3 buffer and filling materials is essential for the reliability of the safety case. The authorities must have the necessary high-level expertise available on the performance of these materials and its effect on long-term safety. The bentonite buffer is an essential part because if the buffer is not functioning as planned, the capsule inside it can me damaged by e.g. increased corrosion. Bentonite or other clay materials are also likely used as a filling material for the tunnels and closure. There are several research topics on bentonite which are central to the safety of the repository, such as connected THMC (thermos-hydro-mechanical-chemical) processes, microstructure research, erosion, microbial effects, radiation effects, mineralogical changes and the effects of freezing. Monitoring of the buffer and filling materials is also a possible research topic.

3 Proliferation = the spreading of nuclear materials, technology and weapons (into irresponsible hands)

Concrete

The long-term behaviour of concrete structures in a repository environment is an essential research topic in regard to spent fuel, power plant and decommissioning waste because concrete structures will be used in the closure of tunnels and the repository. The chemical interaction of concrete with the environment and the pH rise in groundwater are especially important because the chemical effect of the cement on groundwater can last for a long time after the concrete structure itself has disintegrated. The possible research topics in the KYT2022 programme include for example low pH cement and cement in closure of research cavities as well as the long term effects of radiation on cement (in low and intermediate level waste repositories).

Bedrock

In deep geological repositories, bedrock is the natural environment where the waste is disposed. Therefore, knowing the phenomena involved (e.g. fault zones, fracturing, groundwater flow, groundwater chemistry microbiology and radionuclide migration) forms the basis for safety evaluation. In this regard, the rock stability and transport properties are important. Mechanical questions concerning excavating can also form possible research topics. Retainment properties, rock model uncertainty evaluation, rock fragmentation and its geological background, radionuclide transport modelling and groundwater flow modelling are all possible research topics for the KYT2022 programme. Hydrogeological and hydrochemical changes and radionuclide behaviour on barrier interfaces are further possible research topics.

Biosphere

A review of radionuclide transport in the biosphere is necessary because the exposure of people and other living organisms to radionuclides released from the radioactive waste happens in the biosphere. The evaluation of different exposure routes over thousands of years also requires evaluations of biosphere development, which includes the effects of ground surface elevation on coastal areas, climate change and the changes due to future glacial periods. Owing to external changes, the current ecosystems will change and develop differently. Understanding this evolution is important.

3.1.3 Power Plant Waste Management

The management of power plant waste formed in power plants includes different waste fractions with different activities from very low-level to intermediate-level activity. In Finland, the management method for power plant waste is to be geological final disposal. For the lowest activity level waste, other options could be used, such as geological disposal of very low-level waste. For this, the understanding of the biosphere described above is highly important, because the delaying effect on radionuclide transport in the bedrock is essentially omitted.

New technical solutions in the nuclear power plants will also possibly change the quality of the radioactive waste to be disposed of and it is possible to take this evolution into account in the KYT programme. Solidification of the liquid waste (cement, geopolymers, etc.) and the research related to reducing the volume of waste, e.g. with thermal processing, also serve as important elements of the research programme topic. Decontrolling the very low-level waste from monitoring is also related to the reduction of the waste amount. Formation of gas, its transport and radiological effects are related to the topic of power plant waste management.

In the final disposal facilities for the low-level and intermediate-level waste, there are many cement structures and cement waste packages as mentioned in section 3.1.2. For this reason research on long-term durability of cement will be useful in the KYT programme. Besides the mechanical integrity of the cement structures, the stability of the high pH environment caused by cement is also interesting, because high pH slows the corrosion of metallic waste. The effect of alkali-silica reaction in final disposal structures is an important study subject.

3.1.4 Management of Decommissioning Waste

No nuclear power plants have yet been decommissioned or demolished in Finland. However, planning of the decommissioning of nuclear power plants has been under way for many years. The decommissioning project for VTT's research reactor (FIR1) is the first Finnish decommissioning project to be started and it is also seen as useful learning place for KYT.

Many other countries have previous experience of decommissioning. Options that have been used and studied in other countries but untapped in Finland may

emerge while evaluating possible solutions for nuclear waste management, e.g. geological final disposal or new technical pre-disposal methods.

Prior to the final disposal of decommissioning waste, it is necessary to determine exactly the radiochemical composition of the waste. During the decommissioning period, a considerable amount of large metal and cement waste is formed which needs fast and reliable sampling and characterization methods to determine the inventory of the radionuclides. Such waste includes hardly detectable radionuclides whose detection requires reliable analytical methods and authenticated computation. It is important to develop the know-how and methods for this while the first Finnish reactors are moving towards decommissioning. In addition, efficient methods to exempt waste from monitoring can also bring new perspectives to waste management.

For the final disposal of decommissioning waste the principles and methods are similar to other low and intermediate level waste management, and for the biosphere and cement structure parts, similar to final disposal on spent nuclear fuel. These were described in the above paragraphs. For the decommissioning waste, it would also be necessary to study the long-term durability of the reactor pressure vessels used as waste packages in the final repository conditions. Combining chemical and mechanical evolution with other processes would bring valuable information about long-term safety.

3.1.5 Management of Other Radioactive Waste

In the KYT programme, other radioactive waste can be studied especially if it is processed, placed in intermediate storage or a final disposal facility located at the nuclear plant site. This kind of waste can be e.g. naturally occurring radioactive material (NORM), cast-off sealed sources including high activity sealed sources (HASS) and the radioactive waste formed during or following their use.

NORM waste usually refers to waste which contains uranium and thorium with their daughter nuclides. NORM waste is subject to the provisions of the Nuclear Energy Act if it is classified as nuclear material or nuclear waste. Nuclear waste refers to radioactive waste formed or followed by the production of nuclear energy. Because the use of nuclear energy also refers to mining and enriching of ores, the purpose

of which is to produce uranium or thorium, this kind of activity can generate nuclear waste in the event that certain conditions set in the Nuclear Energy Act are fulfilled. The producers of NORM waste are responsible for managing the waste they produce.

Sealed source refers to a source of radiation that contains radioactive material and the structure or properties of which prevent the spreading of radioactive material into the environment in the designed operational conditions. Sealed sources need to be withdrawn from use when they have reached the end of their technical lifetime. At the moment, sealed sources are put into interim storage or the final disposal facility at Olkiluoto based on the agreement between TVO Oyj and the Ministry of Social Affairs and Health.

Some of the sealed sources with the highest activities cannot be returned abroad to the producer or supplier and are left in Finland to await decommissioning. Finland does not have a final disposal site accepted for HASS sources and it remains to be studied what kind of solutions and requirements would make their final disposal at nuclear power plant sites possible.

3.1.6 Key Topics Related to the Safety of Nuclear Waste Management

Various research topics on nuclear waste management safety that have been studied in earlier KYT programmes were presented above. Many topics, e.g. the sub-systems of final disposal, have been studied in detail and we have learned a lot about them. However, for the evaluation of overall and especially long-term safety it is necessary to study e.g. the technical barrier system as a complete entity through coordinated collaboration of multiple fields.

In the KYT2022 programme, there are various new interdisciplinary research topics or aspects of topics researched earlier that are of interest which would be best researched in coordinated projects:

- final disposal concept, which can include waste characterization or durability research of the pressure vessel in final repository conditions. In this topic, KYT-SAFIR co-operation is possible and the readiness developed could have potential

for international co-operation because decommissioning is getting more and more attention worldwide;
- the mutual interactions of the different parts the barrier system in final repository conditions, e.g. the effect of microbes on the technical barrier system;
- the effect of the most intense transient phase (e.g. heat production of the spent fuel for a few thousand years) on the technical barrier system after closure of the final disposal facility.

Coordinated projects can also include other topics, and the aforementioned list is not exhaustive.

Besides the coordinated projects, one key topic is underground final disposal of low-level waste. This is a new topic in the KYT programme, but internationally, underground final disposal facilities already exist. According to a graded approach, the final disposal of low-level waste close to ground level would make the technical barrier system proportional to the lowly classified radiation risk of the waste.

3.2 Feasibility of Nuclear Waste Management

In Finland, development of the final disposal system for nuclear waste has advanced significantly by international comparison, and the feasibility of nuclear waste management has become one of the focus areas of national research. This covers the different actions to achieve compliance, producibility, installability and cost-effectiveness without endangering safety, as well as ensuring retention of national competence and sufficient infrastructure. The evaluation of feasibility and comparison of different technologies are key areas of interest.

3.2.1 Nuclear Waste Management Technologies

The authorities need to have at their disposal real-time knowledge and expertise about the alternative nuclear waste management technologies under development and under research as well as expertise for assessment of various practices and methods in Finnish nuclear waste management. The various options and technologies in nuclear waste management are being reviewed from time to time. In the same context there may arise a need to study new and alternative technical solutions and to improve existing methods. The reliability of implementation in Finnish nuclear waste management can be improved by researching new and alternative technologies for scenarios where the geological disposal chosen as the main alternative would not be realized as planned or new methods would be developed to decrease the amount of waste formed or to make the waste processing method more efficient and safe. This type of research can be best implemented through participation in international co-operation. However, concrete national input and expertise are prerequisites for the participation of Finnish research teams in international research programmes. In this research topic, research can take the form of a review, and several topics can be combined.

In Finland, final disposal of spent nuclear fuel by those responsible for nuclear waste management is based on the fuel being used only once, in accordance with the current legislation on nuclear energy. However, in Finland, too, it is important to be aware of the developed fuel cycles and their possible effects on waste management, e.g. through new waste streams. One possible research topic, which is popular around the world, could be partitioning and transmutation (P&T). This is based on the further development of the reprocessing strategy. In this topic, there is scope for co-operation with the SAFIR programme. In the KYT programme there has earlier been experimental research on the partition of radionuclides.

Finland and many other countries use interim storage in water pools, but a number of different dry storage options exist. Storage in water pools can be scaled to dry storage so that during the initial heat producing period storage would be in water pools. In fact, dry storage has gained ground abroad and is becoming the primary option for new facilities. As part of advanced fuel cycles France, for instance, is considering long-term storage of short-lived radionuclides, separated from the fuel cycle. The storage could last hundreds of years. The safety of storage should be

verified especially if the storage time grows due to e.g. extension of the service life-time of the nuclear facility, or slow progress of disposal projects.

There is an obvious connection in the KYT and SAFIR programmes between the interim storage and reprocessing of spent fuel, because the topic is partly suited to both programmes.

3.2.2 Industrialization of Nuclear Waste Management

The industrialization of nuclear waste management is related to the management of all waste streams. However, the research focus in final disposal facilities varies at different phases of their life cycle.

The maintenance readiness of low and intermediate level waste is advanced, whereas in the case of spent nuclear fuel, the planning within the KBS-3 concept still include the opportunity to develop various materials and manufacturing methods and to study their effects on long-term safety. Processing of low-level and intermediate-level waste so as to diminish its volume and make the waste insoluble is one research topic of particular interest. Especially in case of decommissioning waste, there are still considerable opportunities for comparing different materials, manufacturing methods and the structural alternatives for final disposal, together with their effects on long-term safety.

3.2.3 Development of Nuclear Waste Management Infrastructure

Nuclear waste management research, as with other research, requires a high standard of experimental equipment. As part of the KYT2018 programme, the construction of national infrastructure to VTT's Espoo facilities was supported financially. Further development of the research infrastructure is also part of the KYT2022 programme. Financing of the main instruments of the VTT Centre for Nuclear safety from the funds of the State Nuclear Waste Management Fund will continue until 2020 and funding for the cost of the premises runs until 2025.

One of the challenges of the KYT programme is to ensure that the modern equipment at the VTT Centre for Nuclear Safety can serve the programme's experimental research projects as well as possible. In addition to the Centre for

Nuclear Safety, Finland has other research infrastructures that have been generally developed with the funding of the research facility in question. In this respect, the object of the KYT programme is to map the other infrastructure applicable to nuclear waste research and its national usability. In the same context it is useful to establish the needs concerning this infrastructure. One challenge following this will be to form a network of national infrastructures which could serve to support the experimental projects of the programme.

With a national infrastructure network in place, it would be much easier to coordinate the development of the infrastructure in the future. The KYT2022 programme's research infrastructure development projects could be funded during the research programme period throughan application made as part of the other projects on research, research infrastructure or supplementary education. Otherwise, the development of research infrastructure will continue in later research programmes.

3.3 Acceptability of Nuclear Waste Management

The purpose of the sociological research concerning the acceptability of nuclear waste management is to produce information about the acceptability of nuclear waste management and the whole nuclear energy industry in Finland, and how this changes at different phases of the nuclear plant projects, as well as to produce efficient tools and methods for the discussion of acceptability and to increase the know-how and interest among citizens. The diverse conception among different interest groups concerning the uncertainties, risks and safety of nuclear waste management can have a substantial impact on acceptability. Sociological research needs to concentrate on topics which may become part of societal debate in the years to come as well as topics which repeatedly come to the fore. The acceptability of the nuclear waste management can be viewed from several perspectives, one of which is the experiences and opinions of the authorities concerning nuclear waste management. It is also important to consider the acceptability of nuclear waste management by the public at large, because the values and expectations of the whole of society will affect decisions made by the Government.

The acceptability of nuclear waste management can be also viewed through the concept of the overall benefit to society set out in the Nuclear Energy Act. Nuclear waste management requires political and societal acceptance in addition to technical know-how. Consideration of the overall benefit to society gives decision makers the chance to study the issues (e.g. construction of the nuclear plant) from as wide a perspective as possible. The concept of overall benefit is not defined in detail in the Nuclear Energy Act, but the overall benefit to society is reviewed separately for every project, and it can vary over time. Hence, the concept of overall benefit to society can be an interesting topic of societal research.

The overall benefit to society also takes into account the safety of nuclear energy. It must not present danger or harm to people, the environment or property. In the Nuclear Energy Act, safety is also separately highlighted as a general principle because the use of nuclear energy must always be safe and no consideration can be given to expediency. Safety has also been recognized as a significant factor in people's opinions about the acceptability of nuclear waste management. Thus the coupling of safety culture to the acceptability of nuclear waste management cannot be emphasized enough. A research topic that may be of interest is how the safety case (STUK2018) produced to prove the safety of nuclear waste management is used (or how it can be used) in the acceptability discussions. The state of the safety culture of the companies implementing nuclear waste management as well as the success of communication can significantly affect the acceptability of nuclear waste management.

The overall benefit to society must be realised across the full life cycle of the nuclear waste facility. The life cycle of a nuclear plant project is typically several decades, and as far as the encapsulation and final disposal facilities are concerned it is over one hundred years. In Finland, the nuclear power plants in use will come to the end of their life cycle over the coming decades.

Over the coming decades, decisions will be made as to whether Finland will have one final disposal facility for spent nuclear fuel or several such facilities. The final disposal of spent nuclear fuel is expected to start at Olkiluoto in the 2020s. The nuclear waste management of spent nuclear fuel has been an important societal research topic during the KYT2018 research programme and it is practical to continue this way. Interesting topics are:

- realized ethical and public discussion;
- industrialization of the final disposal plans;
- feasibility of the final disposal;
- the need to control and monitor the final disposal facility after closure;
- the credibility and preservation of information.

The amount of public discussion about nuclear waste management varies by time and place. Also, the amount of discussion affects the acceptability of nuclear waste management. The discussion abroad might also affect the acceptability in Finland. The long-term duration of final disposal also includes questions about the inter-generational fairness, in other words what kind of burden is left for future generations in the form of nuclear waste and who is responsible for the possible long-term costs. The long period of time involved also raises questions about the reliability and preservation of information. How can we ensure that the information about the final disposal facility will remain long enough into the future and that the information will still be understandable? The responsibility for nuclear waste is transferred to the government when the closure of the final disposal facility is accepted. After closure, the government can conduct observation and monitoring when they consider this practical. There are few existing plans and methods concerning the period after closure and these will be developed in the coming decades. Besides the decisions made on nuclear waste management in Finland, acceptability can be affected by the prevailing nuclear waste policies of the EU and its key member countries.

It might be difficult to separate the discussions of acceptability of nuclear waste management from the acceptability of the use of nuclear power plants. Thus, the sociological research related to nuclear waste management can be seen as part of a bigger entity that also includes the safety and acceptability of nuclear power plants. There will also be an opportunity for co-operation with the SAFIR research programme, which will open up a wider perspective.

3.4 Segregated Projects

In the KYT2022 programme, funding can be provided for segregated project proposals meeting the general goals of the research programme, even where they are not directly related to the aforementioned research topics. The segregated project proposals are evaluated against the goals of the research programme.

3.5 Other Funded Activities

Besides the research topics mentioned above, the KYT research programme is funding the expenses of programme coordination. The coordination is organized as a separate administrative project. In addition, funds can be reserved for the administrative project to be used to fund smaller scale projects than research projects. These small projects need to be important and topical according to the steering group of the research programme. The steering group will supervise and guide the implementation of these small projects.

4 Reporting and Information Exchange of the Research Programme

Within the research programme, an annual plan and an annual report will be published. The annual reports are written in Finnish. The research programme's annual plan presents the research projects approved for financing, alongside their key content and planned objectives. The summary form for every project will be in the attachment to the annual plan. The annual report presents the actual results obtained in the projects and how the research objectives were met. The summary forms, by project, will be in the attachment to the annual review.

After the end of the research programme period, a final report will be published presenting the results for the entire programme period. The final report will be published in Finnish and it will be translated into English. Research project results obtained within the KYT programme must be publishable (Nuclear Energy Act, section 53d).

Research programme results related to various topics will be discussed at thematic seminars, which will be arranged when necessary. Each thematic seminar focuses on one topic or a few topics at a time.

If necessary, joint seminars will be arranged in co-operation with the SAFIR programme. Possible joint topics could be overall safety, concrete studies, questions of spent fuel, and questions concerning society.

At the end of the research programme period the research programme results will be presented and discussed at a final seminar.

The research programme website (http://kyt2022.vtt.fi/) and email are the primary means of communicating about the programme.

5 Co-operation

To avoid overlaps, the KYT programme requires that research conducted under the programme is well coordinated with other nuclear waste research6 performed in Finland. Awareness of the contents of Posiva's research programme is particularly important, since it is Finland's most extensive nuclear waste management research programme (see e.g. Posiva 2015). The next research programme, for the years 2019–2021, by Posiva and its owners is going to be published at the end of September 2018. Topical projects within Finnish nuclear waste management research are also described in annual reports prepared by the nuclear industry (see e.g. Posiva 2018).

The KYT programme will closely monitor the corresponding national research programme (SAFIR) focusing on nuclear safety and especially the topics common to the KYT and SAFIR programmes. Possible common topics between the programmes have been highlighted as illustrative examples in this framework programme, e.g. overall safety, intermediate storage of nuclear waste, spent nuclear fuel, cement research and acceptability of nuclear power/waste management.

The co-operation between these research programmes aims to avoid blind spots, to encourage effective utilization of the knowledge and equipment developed, and to avoid overlaps. After the planned merger between the programmes, there will be a common platform for co-operation.

Although the KYT programme is a national research programme, the research itself is international in nature, being based mostly on individual researchers' personal networks. The aim is to encourage international co-operation between individual research projects, such as participation in relevant EU or other international research projects. This is because such projects facilitate participation in broad

international multidisciplinary consortia that would probably be beyond the reach with only Finnish financing.

The KYT programme encourages active participation in international expert workgroups, because they offer a channel for communicating with key organizations within various countries concerning the overall status of Finland's nuclear waste programme and nuclear waste research. They also rapidly provide information on the general status of other countries preparing nuclear waste management. The OECD/NEA, IAEA and NKS expert groups are key forums for Finland.

Participation of foreign researchers in the KYT programme is possible in common projects conducted with a Finnish research group. Through the Finnish research group, the utility of the project in terms of Finnish nuclear waste management would be increased because Finnish nuclear waste management expertise would be channelled into the project.

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Finnish Research Programme on Nuclear Waste Management KYT2022

Framework Programme for the Research Period 2019–2022

KYT2022 is the research programme of the Ministry of Economic Affairs and Employment, where the objective is to ensure that the authorities have sufficient levels of such nuclear expertise and preparedness that are needed for comparison of different nuclear waste management methods and technologies. The content of the KYT2022 research programme, described in this framework programme, is composed on nationally important research topics such as the safety, feasibility and acceptability of nuclear waste management. The framework programme has been prepared by a planning group named by the Ministry of Economic Affairs and Employment. The framework programme is valid for 2019–2022.

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