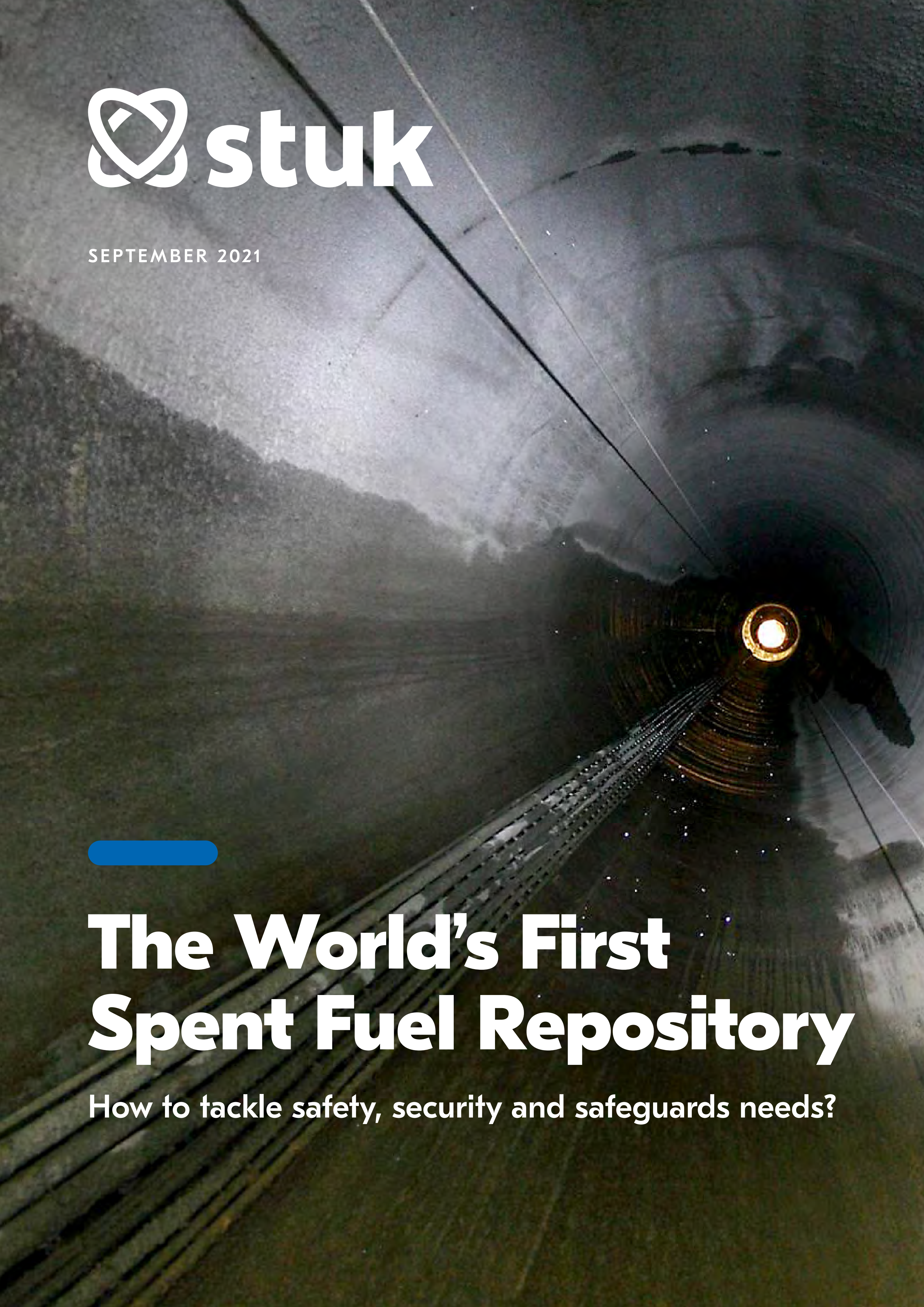

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The World's First Spent Fuel Repository

How to tackle safety, security and safeguards needs?

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Cover picture: Vertical shaft for canister hoist system, that will transfer disposal canisters from the encapsulation plant into the repository at 420 m depth. Picture: Posiva.

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Introduction

How to dispose of spent nuclear fuel safely and permanently? This is one of the fundamental questions related to the use of nuclear energy, that has been waiting for an answer since criticality of the first commercial reactors some sixty years ago. Also, in Finland, discussion on the question of nuclear waste was on the public agenda already when the first reactor was commissioned in the late 1970s and nuclear waste management policy and strategy were actively developed on the national level.

In 1978, the Finnish Government decided that each producer of nuclear waste is responsible for the management of spent nuclear fuel. This decision was the beginning of a long process, the result of which is the world's first spent spent nuclear fuel repository Onkalo, where the final disposal of spent nuclear fuel inside the Finnish bedrock is expected to start in 2025.

This paper describes from the regulatory perspective how Finland changed the game and how Finland is developing a safe[1] and sustainable solution for disposal of spent nuclear fuel. It will explain how this became politically acceptable, how the long-term safety of the solution is being demonstrated and how regulatory challenges related to safety, security and safeguards are being resolved in this first-of-its-kind facility. In broad terms, it will illustrate how the progress in geological disposal has been made possible in Finland and further highlight topical issues that are of interest to professionals and policymakers.

The first chapter is focused on public acceptance and development of nuclear waste management policy and strategy in Finland. The second chapter explains how the long-term safety of the final repository has been handled and what the supporting technical solutions are. In the third and final chapter, an overview of safeguards of the disposal process is provided. Safeguards, a prerequisite for peaceful use of nuclear energy, is a topic of utmost importance also in the last leg of the nuclear fuel cycle.

The scope of this short paper is rather limited and far from complete, but hopefully it manages to pass on certain lessons: responsible decision-making and a long-term political commitment to the chosen method, together with the research and development of the technical solution and enabling regulatory framework, are the keys for accomplishing the difficult task of disposing of spent nuclear fuel safely and permanently.

1 Including safety, security and safeguards.

1. Development of the nuclear waste management policy and strategy in Finland

In Finland, the first four operating nuclear power reactors were commissioned in the late 1970s and early 1980s. Nuclear waste management policy and strategy were actively developed and implemented from the beginning. A nuclear waste management policy generally includes the defined safety and security objectives, arrangements for providing resources for spent nuclear fuel and radioactive waste management, identification of the main approaches for the management of the national spent fuel and radioactive waste categories, policy on export/import of radioactive waste, and provisions for public information and participation. The strategy then sets out the means for achieving these goals.

The first major decision on principles of waste management was made by the government in 1978. According to this decision, each producer of nuclear waste is responsible for the management of spent fuel and other radioactive waste generated in connection with their operations and for the costs incurred. At this stage, permanent exportation of the Spent Nuclear Fuel (SNF) or exportation for reprocessing were considered. The decision also set priority for the Research and Development (R&D) activities related to nuclear waste management. These activities were to be carried out and funded by the waste producers and the R&D to be supervised by the Ministry of Economic Affairs and Employment of Finland.

The first operating licenses for the Nuclear Power Plants (NPP) were granted for a short term, five years or less, and all licenses were due to expire in 1983. One of the reasons for short term licenses was unsolved issues in waste management. In 1983, the Finnish Government made a general decision on the objectives and schedules of the R&D activities concerning nuclear waste management at the existing nuclear power plants. The 1983 decision required that power companies had to carry out R&D for domestic disposal of spent fuel as a backup plan for the permanent exportation solution. It also set a time schedule for this domestic spent fuel disposal option: a site shall be selected by 2000 and disposal shall be operational by the 2020s.

In addition to the R&D supervision, general waste management principles must be approved by the ministry. In the approval, the ministry must set an appropriate time schedule for the waste management actions. This gives the ministry a strong tool for guidance on every nuclear waste producer.

The R&D for domestic SNF disposal was required in the beginning only from the NPP operator and licence holder Teollisuuden Voima (TVO) since the other Finnish nuclear power company Fortum (or its predecessor IVO) had contracted with Russia (then the Soviet Union) on reprocessing of the SNF from its Loviisa NPPs. In the early 1990s it became obvious that it would be nearly impossible for TVO to find a suitable international SNF disposal solution. At the same time, opinions in Finland were strongly calling for Finland to take care of the nuclear waste it produced. This led to a change in nuclear energy legislation to ban both export and import of nuclear waste in 1994. Consequently, Fortum had to start the R&D work for domestic SNF disposal and in 1995, TVO and Fortum established a joint company, Posiva, to perform the SNF disposal related R&D work and to implement the SNF disposal project.

Licensing process

In Finland, all major nuclear facilities follow a similar stepped licensing process which starts with the Environmental Impact Assessment (EIA) process. The first major licensing step is the decision in principle which is followed by the construction license, the operating license, and finally the decommissioning license. The nature of the decision in principle is political, including public consultation. The guiding principle is that the proposal must be in accordance with the overall good of society, but it also sets up a technical framework for the solution. In the decision-in-principle phase, STUK as the safety regulator gives its preliminary safety appraisal of the proposal. The hosting municipality must also give its approval for the project in this phase – which in practice means that the local community has a veto right over the project. Decision in principle is made by the Finnish government but the decision must be ratified by the Finnish parliament.

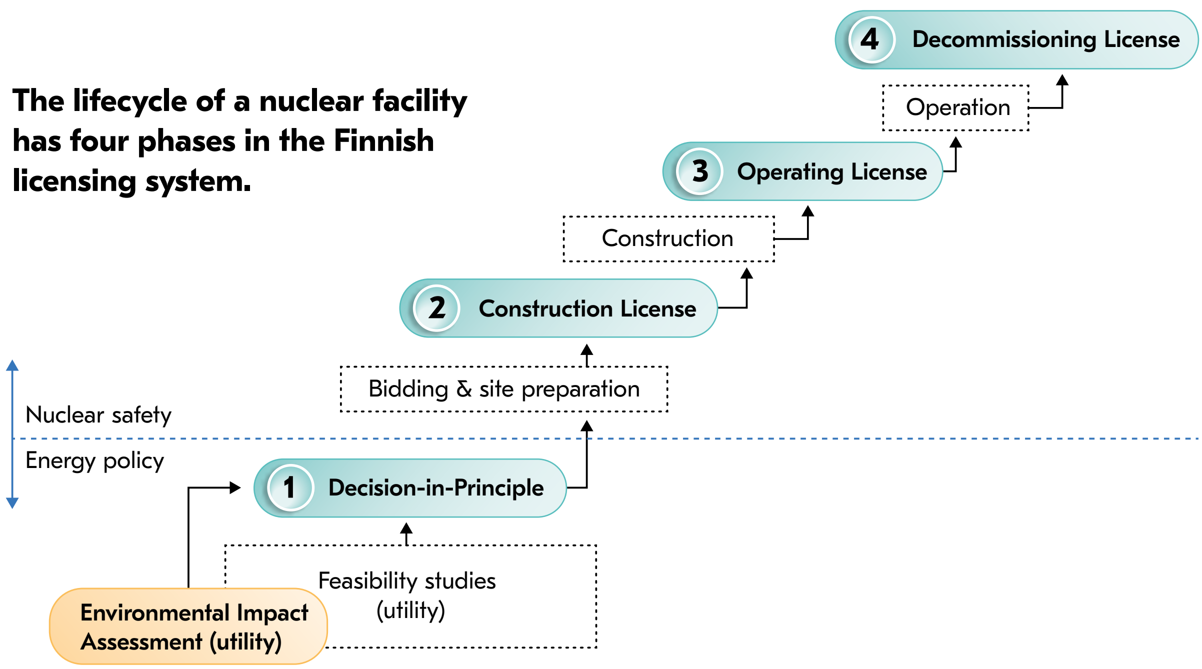


FIGURE 1: Licensing phases of a nuclear facility. STUK assesses safety at every licensing phase.

In SNF disposal, the EIA process was carried out in 1998–1999 and, after negotiations and hearings, the decision in principle was made in 1999–2001. In the parliament's decision in principle, Olkiluoto was selected as the disposal site. The decision also set the disposal depth and concept and gave permission for Posiva to construct the underground rock characterisation facility which will be part of the future disposal facility.

The following construction and operating licenses are more technical. The licences are granted by the Government but STUK will assess safety in each licence phase, in other words, whether the proposed nuclear facility fulfils the requirements set for the safety of the use of nuclear energy. After the licenses are granted, STUK will oversee the construction work and the operation of the facility. Posiva submitted the construction license for the SNF encapsulation facility and the disposal facility in 2012 and the government granted the license in 2015. Construction works have proceeded and Posiva is planning to submit the operating license application in the end of 2021.

STUK as the safety regulator in the spent fuel disposal project

In a spent nuclear fuel disposal project, time frames are usually long and in the beginning the role of the regulator is not always clear. The implementing organization could do R&D work for decades before it becomes a license applicant.

In Finland, the responsibility for the oversight of nuclear waste disposal R&D work rests with the Ministry of Economic Affairs and Employment. Based on the legislation, waste producers report to the ministry every third year on the R&D work done and the near-future plan. To support the review, the ministry must acquire STUK's statement on the R&D report.

In addition to the review of the R&D report, STUK followed the progress of the SNF disposal R&D work in more detail during the site selection process. During the decision-in-principle phase, STUK made a preliminary safety assessment[2] of the SNF disposal project. Construction of the underground rock characterization facility started after parliament's decision in principle and STUK regulated the construction similarly as other nuclear facilities because it was planned to be part of the future disposal facility. The construction license application and the following construction have been reviewed and regulated according to STUK's normal procedures.

Continuous safety evaluation work (including security and safeguards) has been an important tool for STUK to timely give its opinion to the waste producer and to build its own competence. To support the reviews, STUK has also used external experts on specific disciplines. During the progress of the SNF disposal project, the ministry and STUK have updated the nuclear energy legislation and regulatory guidance several times to meet the needs for timely implementation of the project.

2 Preliminary safety assesment includes, inter alia, safety, security, safeguards and emergency preparedness.

2. Long-term safety of the spent fuel repository

The main principles of the Finnish concept of geological final disposal of nuclear waste are the isolation of waste from the biosphere for as long as possible and the prevention of people from accessing a final disposal facility. The final disposal depth and technical release barriers play a role in both principles. They make it possible to achieve isolation from disturbances in the ground surface environment and radioactive substances have a longer or slower route of migration to the surface of the ground if insulation fails. The risk of unauthorized access is also smaller in deep final disposal compared to near-surface final disposal or storage.

The purpose of isolation is to ensure that the hazardousness (radioactivity) of radioactive nuclear waste decreases during the final disposal to a level that is insignificant for the safety of the biosphere. The activity of spent nuclear fuel decreases rapidly at first but reaches an activity level comparable to uranium ore only after a very long period of time.

The safety of the final disposal of nuclear waste in the long term (long-term safety) is based on release barriers that complement one another. In final disposal according to the so-called multibarrier principle, the non-functionality of one or more release barriers must not compromise the safety of final disposal. Release barriers consist of the natural release barrier (bedrock) and technical release barriers.

Radioactive nuclear waste is processed, packed and disposed of meticulously. In the final disposal of spent nuclear fuel, the nuclear fuel is enclosed in a hermetic copper canister that is placed in a hole lined with bentonitic clay inside bedrock, at a depth of more than 400 metres.

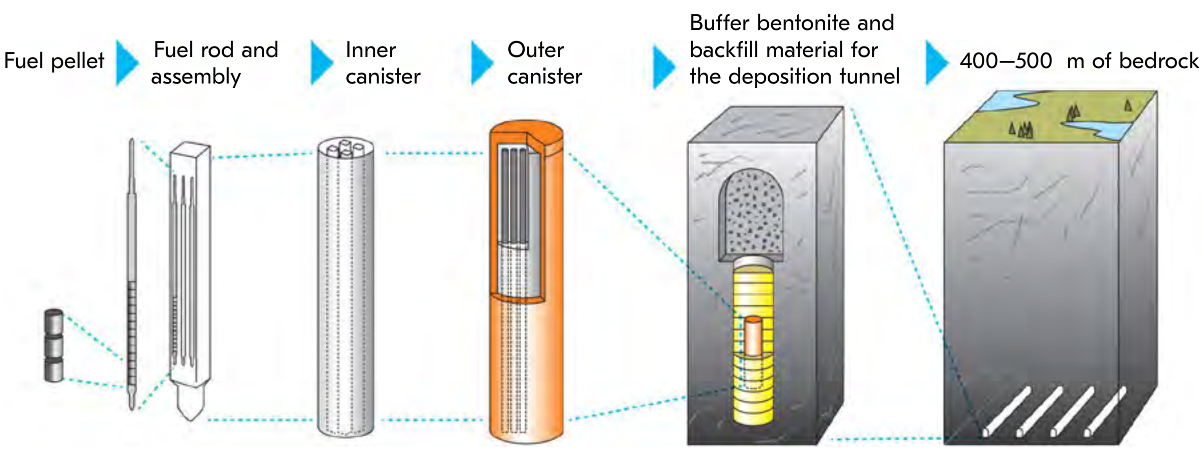
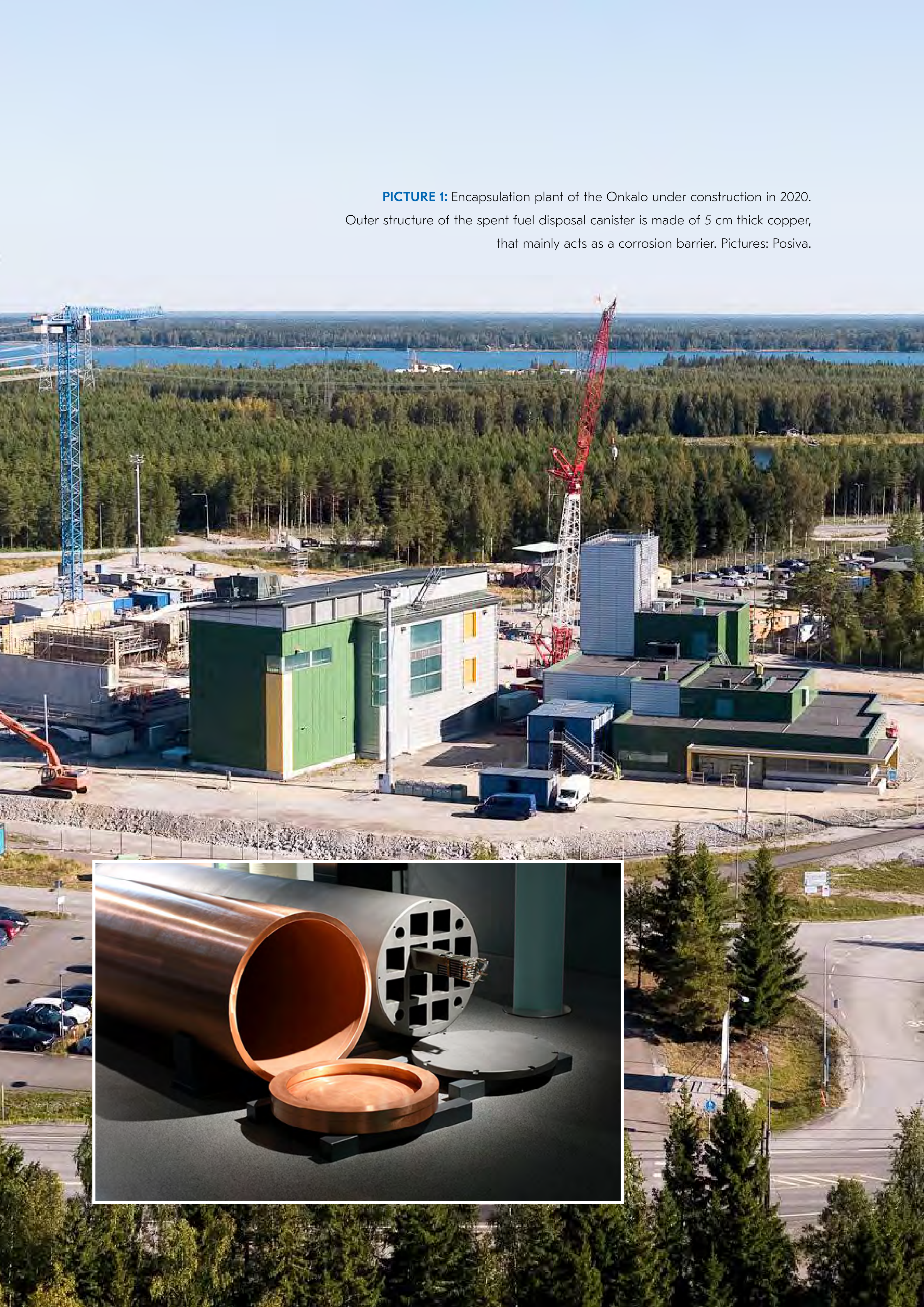


FIGURE 2: Multi-barrier principle of final disposal. Picture: Posiva.



PICTURE 1: Encapsulation plant of the Onkalo under construction in 2020. Outer structure of the spent fuel disposal canister is made of 5 cm thick copper, that mainly acts as a corrosion barrier. Pictures: Posiva.

The purpose of the final disposal canister is to keep radioactive substances inside the canister for as long as possible. The task of the bentonite buffer surrounding the canister is to slow down the process of groundwater getting into contact with the copper canister and, on the other hand, prevent radioactive substances from getting into the rock if the canister leaks. The bentonite buffer also protects the canister from rock displacements. The purpose of tunnel backfilling is to keep the bentonite buffer surrounding the final disposal canisters in place. In addition, tunnel backfilling helps preserve the mechanical stability of the premises and prevent excavated premises from becoming groundwater flow routes. Bedrock slows down the migration of radioactive substances to the biosphere as the flow of groundwater in the cracks of rock is scant and radioactive substances adhere to the crack surfaces and to the bedrock itself.

The quality of release barriers is ensured by defining high quality requirements and extensive inspections for their production. In the construction of a final disposal facility, the goal of maintaining bedrock conditions that are favourable for safety is taken into account. Rock engineering is also subject to high quality requirements.

Long-term safety

Long-term safety refers to the safety in the period after the closure of the final disposal facility. In connection with the assessment of long-term safety, the factors reviewed include, among other things, the adequacy of release barrier design, the significance of the uncertainties that the final disposal solution entails and various scenarios on future developments.

The reliability of assessments of the long-term safety of a final disposal facility is ensured by analysing technical and scientific materials, observations, experiments, tests, and other evidence. The potential radiation effects of final disposal are investigated with safety analysis calculations. The results of the safety analysis are compared with the safety requirements to assess long-term safety.

The future radiation risks caused by final disposal are assessed with scenario-based safety analyses. Scenarios describe potential future developments, such as ice ages or displacements that might cause radioactive substance releases. Analyses involve pessimistic assumptions to compensate for uncertainties related to future developments.

Over very long periods of time, the technical release barriers of a final disposal facility finally lose their functionality. The final disposal solution as a whole aims at ensuring that this does not result in a degradation of the safety level and the remaining radioactive substances would no longer cause hazards for people living in the area.

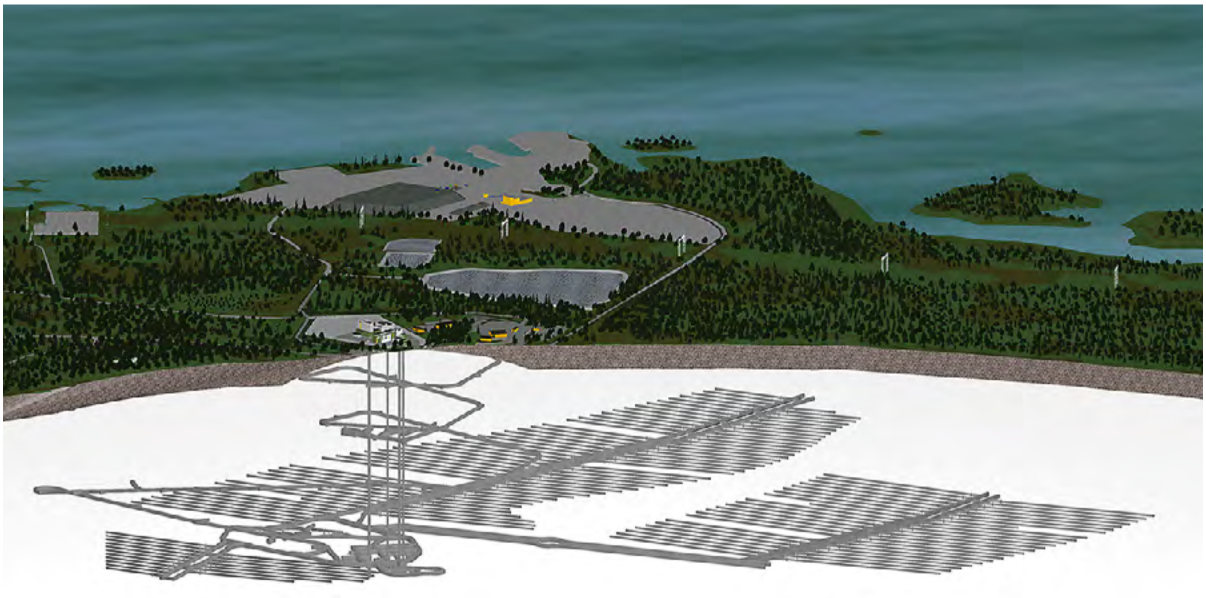
When assessing the safety of the final disposal of spent nuclear fuel in the long term, safety must be assessed as a whole that includes the long-term functionality of the release barriers in the final disposal system as well as the migration, delay and dose calculation of released radioactive substances in the light of different future developments. However, the review of the future inevitably entails uncertainties as the future cannot be predicted. In connection with safety assessment, an understanding must be formed of the uncertainties associated with the whole and, on the basis of it, a view of risks must be formed. When decisions are made about the safety and acceptability of final disposal, risks must be at an acceptable level.

Evaluation of the long-term safety requirements

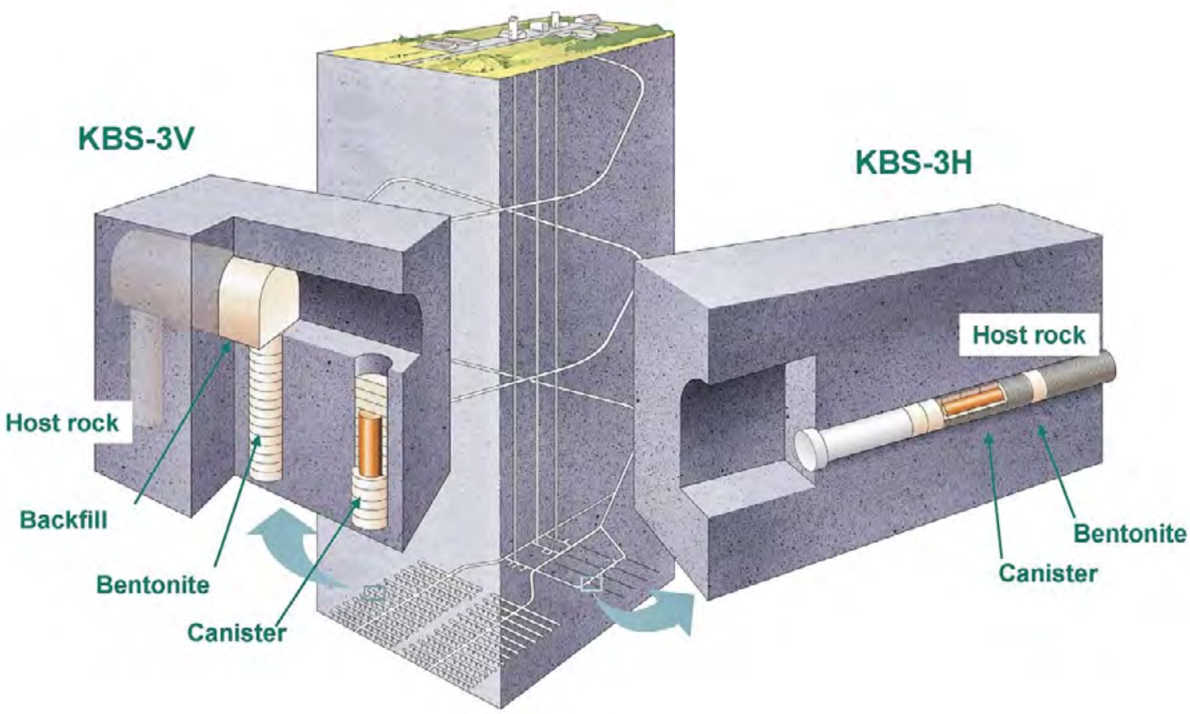
The safety requirements imposed by STUK in Finland require that, in the context of the final disposal of spent nuclear fuel, the technical release barriers isolate the radioactive substances and effectively prevent them from being released to the bedrock for at least several thousands of years, after which the radioactivity of the spent fuel will have decreased considerably. After very long periods of time, the safety of the disposal can mainly be based on release barriers with a sufficiently long stability and their characteristics, such as the bedrock and its favourable conditions and materials that are naturally stable in the disposal environment.

For the purpose of the operating license application, a safety case showing that the repository will satisfy the requirements for long-term safety is being produced. The main components of the safety case consist of a description of the design basis and initial state, an assessment of the performance of the disposal system in different future scenarios and an analysis of the likelihood and consequences of any potential releases of radioactive substances from the repository. The assessment starts from the initial state of the repository and then goes on to study the possible lines of evolution that the disposal system could be subject to in the future. The assessment of the lines of evolution is based on the best available scientific knowledge and data gathered both from Olkiluoto and from different laboratory experiments and technical tests conducted over 30 years.

STUK evaluates the materials related to final disposal and the safety case concerning long-term safety in different permit application phases of the final disposal project. Regarding long-term safety, STUK especially supervises work carried out to demonstrate the performance of the final disposal system, scenario and safety analysis work and their compliance as well as, ultimately, the demonstration of long-term safety and the reliability of the safety case.



PICTURE 2: A schematic presentation of the layout of the underground disposal facility and the network of disposal tunnels for vertical disposal option. Picture: Posiva



PICTURE 3: Disposal tunnel and canisters with both the vertical (KBS-3V) and horizontal (KBS-3H) disposal options depicted. Picture: Posiva.

3. Safeguards at the final disposal facility

Safeguards are a prerequisite for all use of nuclear energy in Finland, i.e. use of nuclear materials and performing of nuclear activities shall be done as required and obliged by the international treaties and agreements.[3]

STUK is the National Authority in the Finnish control system of nuclear materials (state system of accounting for and control of nuclear materials, SSAC) with the purpose of carrying out the safeguards control of the use of nuclear energy that is necessary for the non-proliferation of nuclear weapons as well as the safeguards control that is related to the international agreements on nuclear energy to which Finland is a party.

STUK oversees that any user of nuclear energy has the necessary expertise and preparedness to arrange the supervision and that the user for its own part implements the above-mentioned supervision in accordance with the pertinent regulations. In addition, in the legislation there are requirements for all users of nuclear energy to ensure that the planning, construction and operation of a nuclear installation shall be implemented so that the obligations concerning the control of nuclear material, as provided and defined in the Nuclear Energy Act and provisions issued thereunder, and in the Euratom Treaty and provisions issued thereunder, are met. The facility or any other nuclear installation shall not contain premises, materials or functions, relevant to the control of nuclear materials, which are not included in the design information. Any user of nuclear energy shall have an accounting and reporting system for nuclear materials and other nuclear commodities which ensures the correctness, scope and consistency of information in order to implement the supervision necessary for the non-proliferation of nuclear weapons.

With the view of national legislative objectives and international obligations, Finland is developing a solution for disposal of spent nuclear fuel. Spent nuclear fuel will soon be

3 In the Paris peace treaty in 1947 Finland was required not to hold, produce, or test any kind of atomic weapons. This has been driving force in development of the use of nuclear energy in Finland and since then Finland has been a committed for non-proliferation. Finland was among the first state parties to sign the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) on 1 of July 1968, which entered into force on 5 March 1970. Finland was also the first country to negotiate and sign Comprehensive Safeguards Agreement with the IAEA (INFCIRC/155). The national legislation requires that the use of nuclear energy is safe and does not promote proliferation of nuclear weapons. See: Paju, Petri 2020: Finland and Nuclear Non-Proliferation: Fifty years of implementing the Nuclear Non-Proliferation Treaty. Available at: http://urn.fi/URN:ISBN:978-952-309-491-8

disposed of into the Finnish bedrock at a depth of more than 400 metres, in a manner that makes it practically impossible to recover the material.

A part of the legislative objective is that the use of nuclear energy shall be safe and shall not cause harm to humans or the environment. This supports and complements the security and safeguards objectives. The operator is always responsible for the fulfilment of safety, security and safeguards requirements, and that the necessary information will be timely and correctly provided to national and international regulators responsible for supervision. As a whole, the 3S (safety, security, safeguards) approach is applied to ensure that the abovementioned objectives can be achieved. All three approaches shall be implemented properly and comprehensively, and none of them shall ever fail.

Safeguards by Design

Safeguards by Design (SbD) means that safeguards requirements are taken into account in the early design phase of the nuclear facility construction project. This requires close cooperation and interaction between stakeholders: regulators, inspectorates, owner, operator, designer, and vendor.

- SbD is beneficial for all parties involved.
- SbD can help to avoid extra costs and difficulties associated with fitting safeguards measures in at later stages of the design or construction phases. It can also help to enable and optimize the use of new safeguards measures.

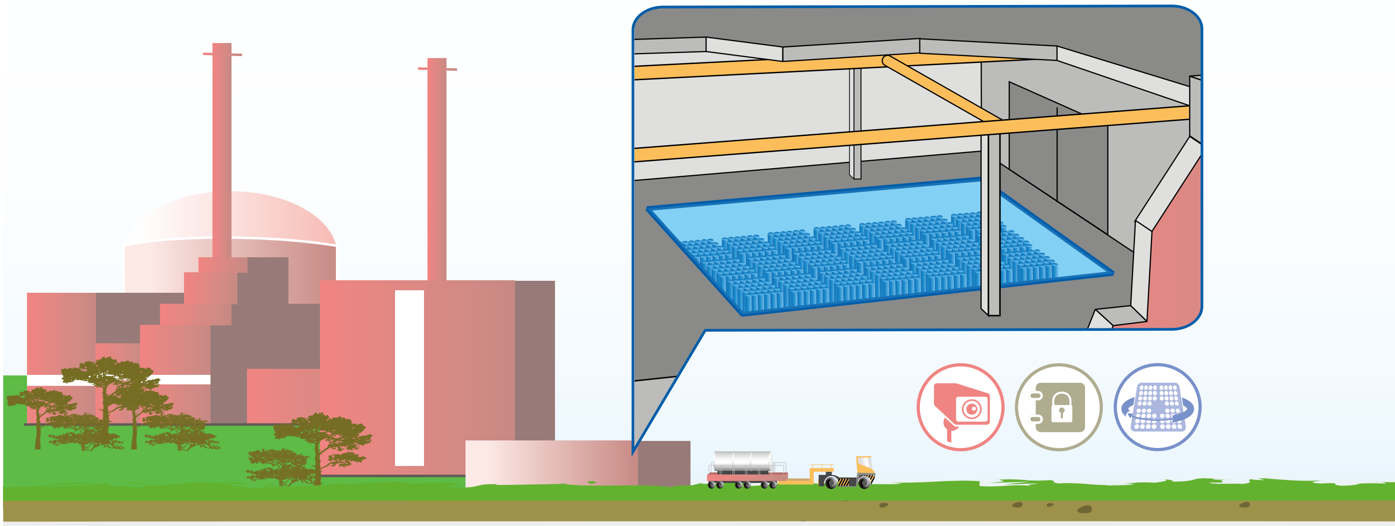
Implementation of safeguards by design is an important approach in developing both national and international safeguards for the disposal of spent nuclear fuel.

PICTURE 4: STUK oversees all phases of construction of the Onkalo at site. White liquide is drill cuttings waste generated during excavation of the bedrock. Picture: Paula Ruotsalainen/STUK.

Nuclear Safeguards in the Final Disposal

1 Spent Fuel Storage at the Nuclear Power Plant

At the spent fuel storage authorities inspect that the spent fuel is consistent with declarations.

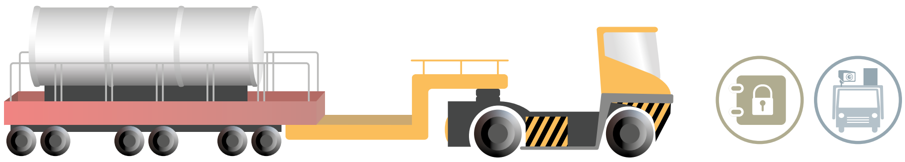


Safeguards Methodology

- Camera
- Seals
- 3D laser mapping
- Seismic monitor
- Passive Gamma Emission Tomography (PGET)
- Kr 85 detector
- Laser curtains
- Ground penetrating radar
- Radiation monitor
- Camera and radiation detector mounted on vehicle

2 Transportation of Spent Nuclear Fuel

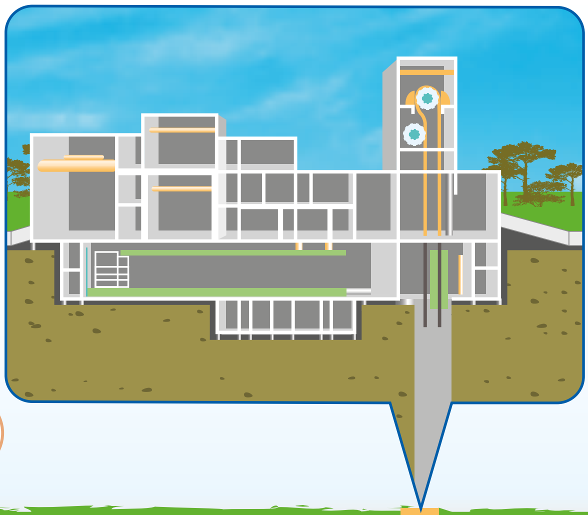
The authorities use seals and monitoring devices to ensure, that spent fuel remains untouched during transfer.

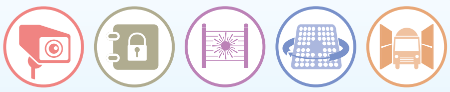


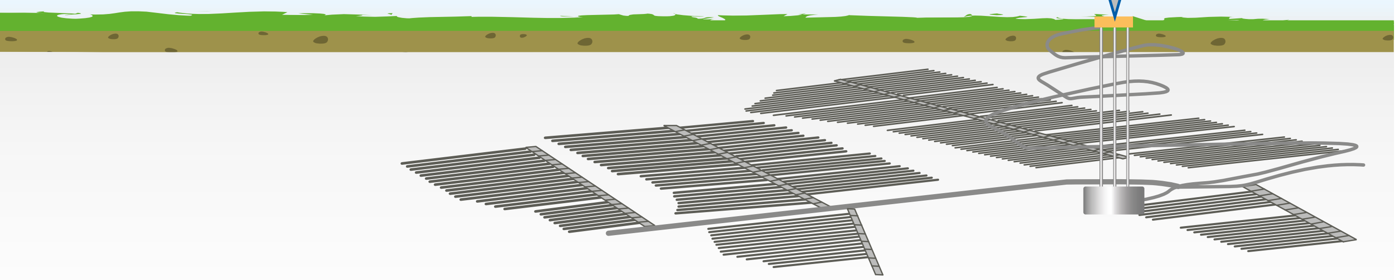
3 Encapsulation Plant

At the encapsulation plant, the authorities ensure that fuel assemblies are placed in the right canisters.

Movement of spent fuel canisters from the encapsulation plant to the final repository is monitored continuously.







The spent fuel repository is located approximately 450 meters underground.

4 Spent Fuel Repository

Inside the spent fuel repository the authorities supervise, that there are no undeclared activities in the tunnels, such as a secret reprocessing facility.

After the spent fuel has been encapsuled and disposed of it can no longer be verified.

Authorities also supervise, that new tunnels are not excavated from the outside to the repository. All entry and exit routes to the repository are monitored.

Monitoring of the spent fuel repository continues also after its closure.

Data retention will be ensured.

Safeguards challenges of disposal can be divided in two separate areas:

1. After placement of the canister into the bedrock and backfilling of the disposal tunnel the fuel is beyond any traditional re-verification methods.
2. The final repository has safeguards relevance even after closure of the facility, in around 2120.

The first challenge is addressed by strict Containment and Surveillance (C/S) and maintenance of Continuity of Knowledge (CoK) throughout the process. All fuel to be disposed of is verified with the best available methodology, before encapsulation. The selected method is Passive Gamma emission tomography (PGET), which is an IAEA safeguards approved method. PGET will be complemented with other technologies as appropriate.

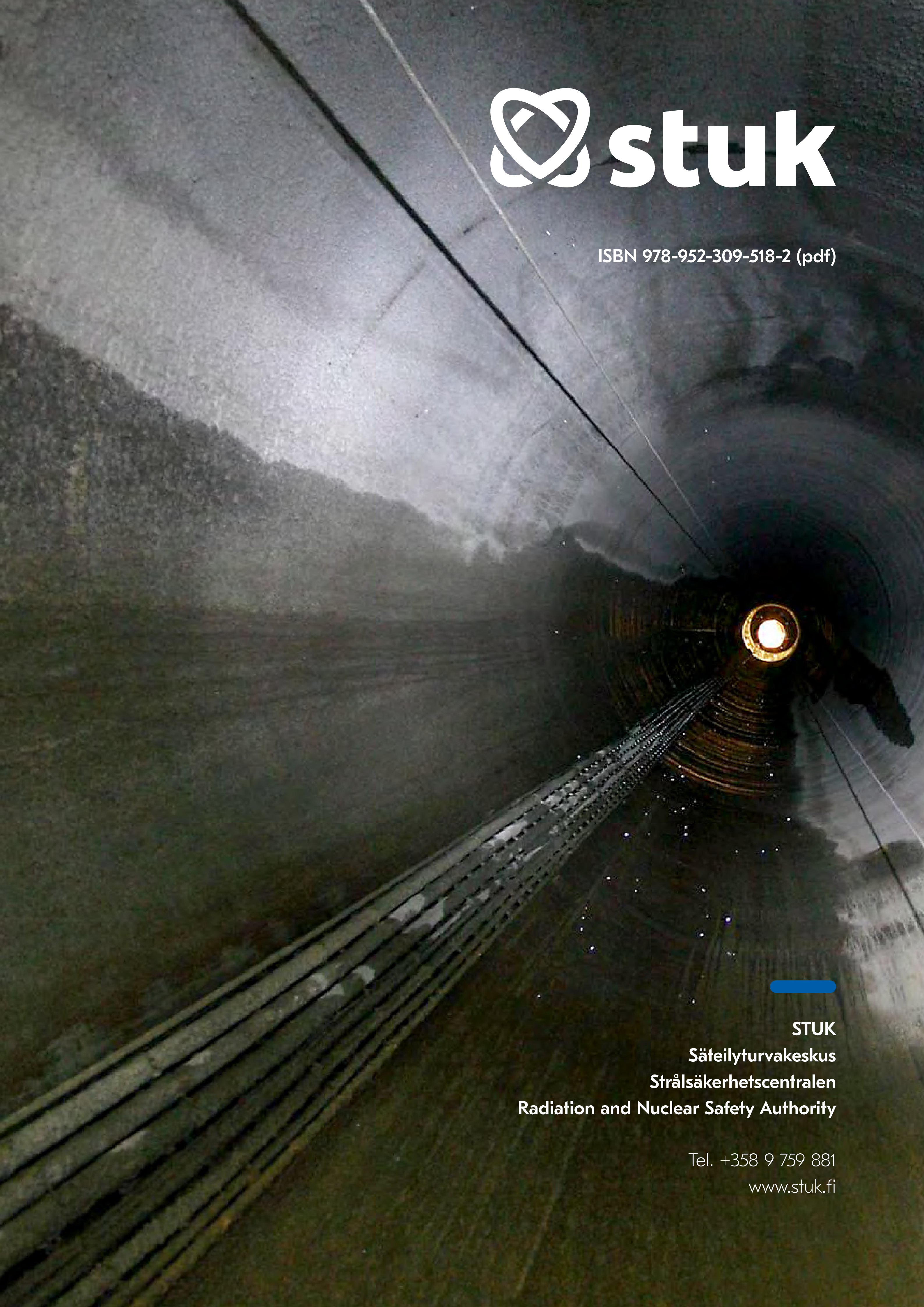
As a result of verification, C/S and CoK, a dataset is generated, which provides future generations with reliable information about the disposed fuel, and they can assure themselves about the content of the repository.

The second challenge is related to the waste management concept that relies on a repository without long-term institutional arrangements after closure. It is obvious that site characterization, construction, operational documents and verification activities will provide the CoK needed for safeguards during the operational phase of the repository. The intact bedrock will provide society with long-term safety and security provisions. However, the question of continuation of post-closure safeguards could create open-ended questions that may cause an undesired burden on future generations. At the moment, answers to these issues are not available, and the debate is not acute yet. There is about 100 years' time to develop new technical tools and create new concepts. By selecting the disposal option, the Finnish society has chosen a way which would resolve the safety issue forever without leaving undue security or safeguards issues for future generations.

Safe way forward

In Finland, while safety, security and safeguards are considered as a basis for making things possible, we also want to confirm that the facility that is being constructed withstands adversity and questioning in an integrated manner. This first-of-its-kind nuclear facility is also a regulatory challenge – and our duty is to confirm that it is built to be safe and regulatory control will continue throughout the whole lifecycle of the facility[4].

4 Planned safeguards measures are illustrated on pages 16 and 17.



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