SPENT FUEL AND RADIOACTIVE WASTE MANAGEMENT IN FINLAND

TIMO SAANIO
Vice President
AINS GROUP

NUCLEAR POWER AND RADIOACTIVE WASTE MANAGEMENT RESPONSIBILITIES IN FINLAND

Roughly half of the electricity produced in Finland comes from nuclear electricity. We have five nuclear reactors in Finland. Three reactors are running in Olkiluoto nuclear power plant and two reactors in Loviisa.

The latest reactor started regular electricity production in April 2023. This new European Pressurized Water Reactor (EPR-type) OL3 produces electricity about 1600 Megawatt (MW). OL3 will for its part guarantee carbon-neutral production electricity at a competitive price for next 60 years.

Four other reactors in Finland started to operate in the late 1970s. Two reactors in Olkiluoto are boiling water reactors. Electrical output of the reactors is 890 megawatts (MW) each. Two reactors in Loviisa are pressurized water reactors with electrical capacity of 500 megawatts (MW) each.

During the years nuclear power plants in Finland have operated very good and reliably. Utilization rates have been excellent. On the other hand, waste management of the spent fuel and radioactive waste is handled consistently, transparently and successfully. Therefore, we believe that nuclear energy plays a major role in the implementation of the Finnish climate and energy strategy.

In Finland funding and sufficient competence for waste management is ensured by nuclear waste management fund. Operators under a waste management obligation pay annually to the fund. The fund has always enough assets to cover the costs of all nuclear waste management actions that still have to be carried out. The fund operates under the Ministry of Economic Affairs and Employment.

Both Teollisuuden Voima Oyj (TVO) and Fortum Power & Heat have their own interim storages of spent nuclear fuel and operating waste repositories for low and intermediate-level waste on their sites. Posiva is responsible for the final disposal of spent fuel from both Olkiluoto and Loviisa power plants, Figure 1.

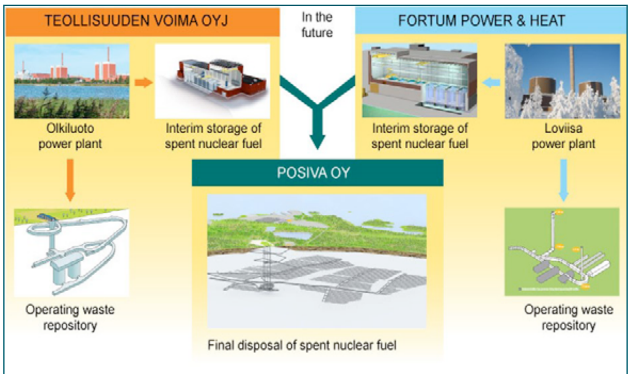

Figure 1. Nuclear waste management responsibilities in Finland.

REPOSITORIES FOR LOW- AND INTERMEDIATE LEVEL WASTE

In Finland it was decided already in the late 1970s to construct two underground low- and intermediate level waste repositories to the power plants sites, one in Olkiluoto and one in Loviisa.

OLKILUOTO LILW REPOSITORY

The low- and intermediate level waste repository in Olkiluoto houses the operational waste from Olkiluoto Nuclear Power Plant. This operating waste is classified into low and intermediate level wastes. The decommissioning waste generated during the dismantling of the plant units will also be deposited in facilities to be built in the same underground complex. Waste is packed into concrete containers and transported to the repository using a radiation-protected vehicle. In the repository, the concrete containers are placed into the LLW and ILW silos, excavated into the bedrock to the level of 70–100 meters below the ground surface. In the first stage, two silos (diameter of 24 m and height 35 m) were built (roughly 90.000 m^3) and they have been in operation since 1992. The underground facility comprises an access tunnel (665 m), unloading tunnel (120 m), construction tunnel (410 m), access shaft (57 m) and the silos themselves, Figure 2. The silos are nowadays half filled.

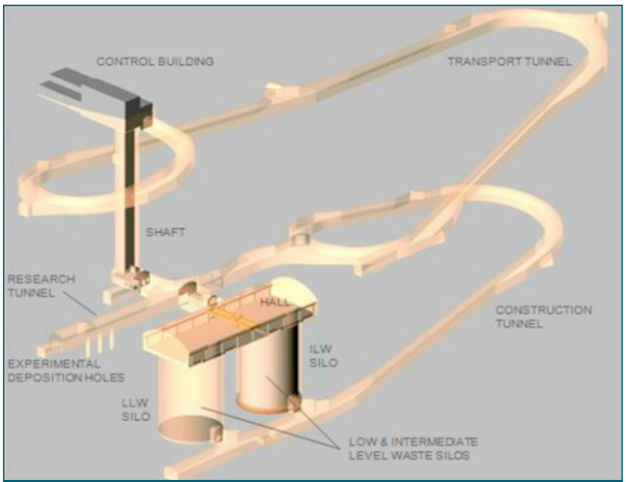

Figure 2. Cross-sectional view of the Olkiluoto LILW- repository lay-out.

LOVIISA LILW REPOSITORY

Fortum Power and Heat Oy dispose the operational waste from Nuclear Power Plant of two reactors into the underground repository on the island of Hästholmen. The radioactive operational waste is classified into two categories - low and intermediate level waste (LILW). The decommission waste generated during the dismantling of the plant units will be also disposed in facilities to be built in the same complex. Construction work began in 1993 and operations in the repository started in 1997. Facility has been extended twice. Currently, the repository consists of the access tunnel, two shafts and four repository vaults at the depth of about 110 meters, Figure 3. Low level wastes are packed into steel drums which shall be disposed in two of the four vaults. The intermediate level liquid waste will be solidified and packed by concreting and disposed into one of the vaults. After completion of all disposal operations the spaces will be backfilled.

FUTURE

Repositories in Olkiluoto and Loviisa have been in operation since 1990s. We have very good experience from the operation of repositories for low- and intermediate level waste in Finland. Current plan is that the repositories will be operated until nuclear reactors in Olkiluoto and Loviisa are shut down. Finally, the decommissioning waste of the nuclear reactors will be disposed in the extension of the repositories. This will be carried out roughly in 2040s or even later. The planned extension for the repositories is shown in Figure 3 (Loviisa) and in Figure 4 (Olkiluoto).

SPENT FUEL REPOSITORY

Finland is on its way to be the first country in the world to start final deposition of the spent fuel from the nuclear reactors. The schedule for the project was set up in the early 1980s aiming to start the operation in the 2020s. Now the repository is almost ready and an operation license application for the

Figure 3. Loviisa LILW-repository and possible extension of the repository. Existing tunnels and shafts are in gray and planned extensions are shown in green [1]. 1 = tunnels for maintenance waste, 2 = tunnel for solidified waste, 3 = room for large components, 4 = silos for reactor pressure vessels, 5 = tunnel for decommissioning waste 1, 6 = tunnel for decommissioning waste 2, 7 = connection tunnel, 8 = personnel shaft, 9 = ventilation shaft, 10 = access tunnel.

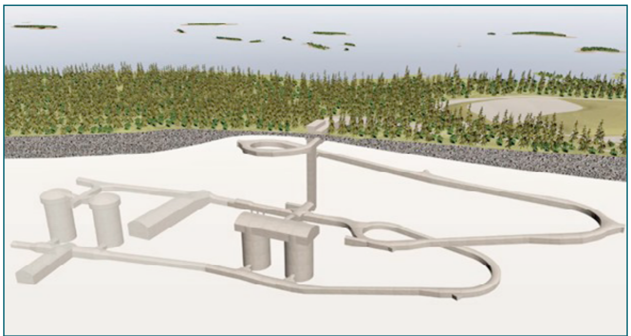

Figure 4. Possible extension of the repository in Olkiluoto. The available rooms are marked in dark grey, and the planned extension is marked in light grey. [2], source: TVO.

repository is being processed at Radiation and Nuclear Safety Authority in Finland. Following chapters introduce site selection process for the repository, technology of the concept and current situation on the site. Site selection process is introduced more detailed in the summary report [3].

SUCCESSFUL SITE SELECTION PROCESS

Already in 1983, the Finnish Government made a policy decision on the management of nuclear waste in which the main goals and milestones for the site selection program for the deep disposal of spent fuel were presented. According to this decision several site candidates, whose selection was to be based on careful studies of the whole country, should be characterized and the site for the repository selected by the end of the year 2000. The main objective of the site selection program was to find a site for disposal of spent fuel which could meet the following demands:

- a safe repository system could be developed on the site,
- the site would keep long-term radionuclide releases within a regulatory limit,
- it was technically feasible to build the repository on the site,
- the repository would be environmentally acceptable during both during construction and post-closure (e.g. it was nec-

essary to consider the implications of additional traffic, the disposal of excavated rock spoil etc. in this analysis),
- the development of a repository on the site would have widespread public acceptability and
- the cost of the repository would not be prohibitive.

In the first phase "site identification survey" during 1983-1985 totally 101 potential investigation areas were chosen from all over Finland. Typical size of each investigation area was 6-10 km^2. After evaluation by authorities, 85 potential investigation areas continued to the next phase.

Geological factors of interest in site selection were topography, bedrock stability, final disposal depth, size of the formation at the final disposal site, homogeneity, rock type, faulting and fracturing, diapiric structures, porosity of the bedrock, sorption, natural resources and erosion. Each factor was scored from 1 (best) to 5 (worst). Based on the scoring, investigation areas were classified into four classes (based on their overall score): I: primary recommended areas, II: secondary recommended areas, III: recommended, but with reservations and IV: not recommended.

Five sites were selected to the preliminary site investigation phase (1987 – 1992). The study area of the sites was about 5 - 6 km^2. The field investigations were executed on these sites according to similar programs divided into four consecutive phases:

- General survey of the geology and hydrogeology
- Drilling of one about 1000 m deep borehole with associated sampling and geophysical logging
- Hydrogeological and hydrological monitoring in boreholes and at the surface, the drilling of four additional boreholes and borehole logging and supplementary surface geophysical measurements
- Hydrogeological and hydrological monitoring, pumping tests in boreholes, rock stress measurements and further analyses of the geochemistry of the groundwater

In the preliminary site investigation phase, generally well-established methods were employed to study the rock mass and the surficial deposits. Wide range of applied geophysical techniques were used and these occupied a prominent position in the preliminary site investigations. The goal in terms of groundwater chemistry was to obtain information on the chemical nature of the groundwater for use as initial data for chemical modelling. The range of measured parameters defined was comprehensive. The overall aim of the preliminary site investigations was to allow selection of two or three sites for more detailed evaluation. This, in turn, required the ability to generate a sufficient number of suitably precise data for each site and the construction of models that could represent the site to an acceptable level, in order to enable fair comparisons to be made.

Based on site investigation phase, three sites were selected to the detailed site investigation phase (1993 – 2000). Change in primary legislation that resulted in spent fuel from the Loviisa power plant having to be disposed of in Finland, had the consequence that the island of Hästholmen was added to the list of potential disposal sites as the fourth site. Spent fuel from the Loviisa power plant had been previously returned to Soviet Union from where the fuel to Loviisa had been bought.

The field investigations were executed according to the area-specific programs. The investigations were divided into three task-groups:

- Baseline investigations describing hydrogeochemical and hydrogeological conditions and the state of rock stress
- Characterizing investigations for the acquisition of complementary data on the properties of the bedrock
- Investigations to confirm that the previous results and hypotheses in the areas are correct.

The environmental impacts of the following components of a repository development program were considered in developing the environmental site selection criteria:

- site investigations at the potential disposal site
- construction of the encapsulation plant and repository
- operation of the encapsulation plant and
- closure of the repository.

Finally in 2000, the selection of Olkiluoto from the four sites investigated during detailed site investigations was based on factors:

- Long-term safety
- The feasibility of repository development
- The possibility of repository enlargement
- Repository operation
- Social acceptance
- Land usage
- The environmental burden
- Infrastructure
- Costs

Even though social acceptance in only one of the factors above, it has been recognized to be very important. Local level acceptance plays a key role when selecting the site. To achieve this, strong presence on the site is needed already in the site investigation phase. Local offices, informative happenings and possibilities for the locals to work in the project enhance possibilities for the successful site selection process.

It is not a surprise that the safety is the key issue also for the public. Finns trust our regulator, Radiation and Nuclear Safety Authority. Therefore, it is important that the regulator actively and visibly participates in the process. It was also noticed that it is easier to gain approval for the final disposal in municipalities that have previous experience of nuclear power.

Public acceptance was crucial for the success of the project. In the Finnish experience, key task to gain public acceptance is building confidence through excellent communication, transparency, open dialogue on the sites with local people and involvement of the regulator in the project.

REPOSITORY OVERVIEW

The spent fuel repository consists of an underground repository at a depth of 400-450 m and above ground service buildings. Access routes are an inclined access tunnel and 4 vertical shafts. Construction works started in 2004 and the facility will start operation in couple of years - the operational time is about 100 years. The encapsulated fuel is transferred to the facility technical rooms in the canister lift, from there to the disposal area via central tunnel and will be deposited in the deposition holes. Holes are bored in the floors of the deposition tunnels and covered with granular bentonite. The underground repository and its components are presented in Figure 5.

The first phase in the construction of the spent fuel repository was an underground rock characterization facility, ONKALO, was excavated at the disposal level. ONKALO was designed and constructed so that it can later serve as part of the repository. The goal was that the first part of the disposal facility will be constructed under the building permit phase in the 2010's and operations will start in the 2020's. The fuel from all five operating reactors has been taken into account in designing the disposal facility. The amount of the spent nuclear fuel is 5,440 tU. The disposal facility is being excavated and closed in stages over a long-term operational lifetime of about 100 years. In the expansion plans of the facility, there is a layout example of the repository for 9,000 tU. This is also the maximum amount of spent fuel in the Decision-in-principle regarding the final disposal of spent fuel. Figure 6 illustrates an example of placement options for 5,440 tU nuclear waste within the repository.

During the operation phase, fuel assemblies are enclosed in sealed metal containers (canisters) with a cast-iron insert and a surrounding copper shell. The heat output of each disposal canister is limited to an acceptable level by always selecting sufficiently cooled fuel assemblies with a suitable heat output for each disposal canister. Once fuel assemblies have been transferred inside the canister, it is filled with inert gas and sealed tightly with the inner steel lid of the canister. The top copper lid of the canister is sealed by welding. The tightness of the weld is ensured visually and by non-destructive methods.

The sealed and inspected disposal canister is transferred via a vertical shaft to the disposal facility's reception station at a depth of about 420 m and from there by vehicle to the repository and a deposition hole. The strong, corrosion-resistant canister is designed to contain spent fuel and to prevent radioactive material from entering the bedrock where it could enter the living environment with groundwater.

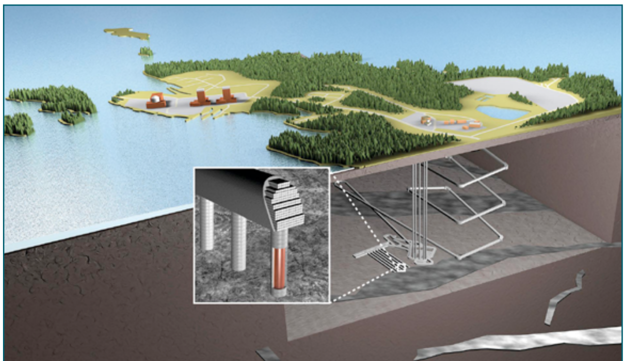

Figure 5. The disposal facility, schematic illustration, source: Posiva.

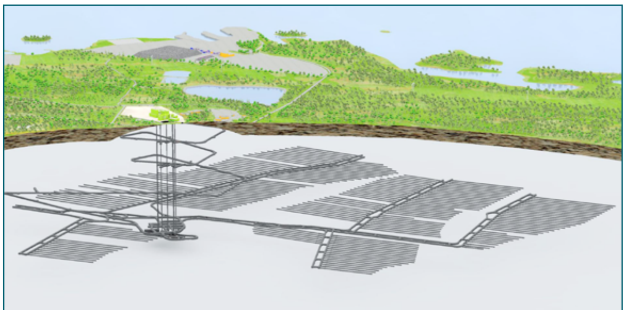

Figure 6. Final disposal facility for spent fuel consisting of several sets of deposition tunnels and central tunnels (forming panels). Figure Posiva.

In the repository, the canisters are isolated from the bedrock by means of a layer of bentonite clay. The purpose of bentonite is to maintain favourable conditions for disposal and isolation of the canister and to prevent as much as possible the effects of groundwater on the canister. It is also intended to prevent and slow down the transport of radionuclides within the bedrock in possible exceptional situations, for example in the event of leakage or breakage of a copper canister [2].

Closure means the closure of the rooms of the repository so that is intended to be permanent. The closure of the repository must be carried out in such a way that the bedrock retains, as far as possible, the characteristics essential for long-term safety. The closure of the repository will be carried out in stages. The deposition tunnels will be closed as soon as the planned number of canisters have been disposed in them, and the closure of the central tunnels will begin decades from now upon transition to the next disposal panel [2].

The deposition tunnels are filled with a granular mixture comprising crushed bentonite pellets of varying sizes. A granular backfill solution ensures the functionality of the buffer surrounding the canister such that the buffer cannot rise from around the canister into the deposition tunnel. The main task of the tunnel backfill installation equipment is to transfer the granular material into the deposition tunnel by filling the tunnel from the floor to the ceiling. During tunnel backfilling, the equipment moves slowly in reverse until the entire tunnel is filled [4].

When all canisters to be disposed of have been installed in the deposition holes and the operating and decommissioning waste from the encapsulation plant has been disposed of, the closing phase of the disposal facility begins. The requirements regarding closure differ from those set for backfilling and closure of the deposition tunnels. The main purpose of technical release barriers, such as the backfilling and closure structures, is to limit the migration of radioactive materials via excavated facilities. For the access routes to ground level and other underground facilities (such as central tunnels and technical facilities), this means, in practice, that the backfill materials and closure structures must prevent the formation of significant flow routes between ground level and the deposition tunnels. The backfill materials and closure structures must also support the surrounding bedrock and prevent the inadvertent entry of people into the facilities. In addition to this, the materials used for closure must not have a significant harmful impact on the performance of the multi-barrier system. The permanent closure of the repository will not take place until the 22nd century.

Retrieval of waste packages from the disposal facility for safety reasons shall be provided for the operating phase of the disposal facility according to the regulations. In addition, the regulator has required clarification of retrievability after closure. Canister retrieval is easiest during the operating phase, estimated to last approximately 100 years, when final disposal is still ongoing. Later the facility will be closed with the backfill and plugs are installed, after which retrieving the canisters from the repository will be more challenging but still possible. The canister design takes into account the need for retrievability.

Design of the repository has been developed systematically over a long period of time in close cooperation with long-term safety assessments and site investigations and characterization. The preliminary plan for phase 1 of spent nuclear fuel repository facilities was produced in 2003 [5] and for phase 2 in 2006 [6]. The repository draft plan was drawn up in 2009 [7]. Extensive description of the repository technology, operation and closure used for the construction license application of the facility can be found in the design report [8]. Lessons learnt has been that very close interaction between design, safety assessments and site investigation is essential. Several steps and iterations are needed to get more information of the bedrock, prepare revised designs and to analyze safety using latest information of the bedrock and revised designs and so on.

ECONOMIC ASPECTS AND HUMAN RESOURCES

The total costs of the spent fuel and radioactive waste management of the Loviisa and Olkiluoto nuclear power plant units (OL1–3, LO1–2) are estimated at approximately EUR 7 billion for the entire lifetime of the power plants (at the 2020 price level). Of this, the costs of spent fuel disposal are approximately EUR 5 billion. The figure includes the disposal of spent fuel, the construction, operation and closure of the overall facility, as well as Posiva's research and development expenses, property taxes and the costs of regulatory control. The costs for the management of operational waste from nuclear power plants are approximately EUR 150 million. The costs of decommissioning the plants are approximately EUR 1.1 billion. The remainder of the costs consist, inter alia, of TVO's and Fortum's research and development costs, interim storage costs, regulatory control costs and taxes [2].

The spent fuel disposal project's impact on employment is expected to be approximately 550 man-years per year at most. During the operational stage, the immediate annual employment impact has been estimated to be about 130 man-years. The employment impacts of the repository are major for the entire region: at most approximately 220 man-years per year. The employment effect on the municipality of Eurajoki and the region will have a significant positive impact on employment in the municipality and region. Also real estate tax paid by the plant has slowly strengthen the municipality's income tax base. This enables a strong annual balance and exceptional possibilities for the municipality [9].

ONGOING WORKS ON THE SITE AND NEXT STEPS

Currently about 14 km of different kinds of tunnels have been excavated. All technical rooms, a spiral-shaped access tunnel, four vertical shafts and the first five deposition tunnels are almost ready, Figure 7.

Next step in the project is the Trial Run of Final Disposal (TRFD). TRFD consists of a full-scale encapsulation and final disposal test with the final equipment under actual conditions except that canisters do not contain spent fuel. The trial run will be used to ensure that the phases related to final disposal work as planned. The Trial Run of Final Disposal physical works will be started during 2024. TRFD will produce significantly more detailed information about the operations in the repository than the earlier tests. Information from the tests will be available for the institutes participating in TRFD.

Figure 7. A deposition tunnel in the spent fuel repository, picture Timo Saanio.

Operating licence application for the repository was submitted to the Ministry of Economic Affairs and Employment in the end of 2021. The application will likely be considered by the Finnish government quite soon.

When operating licence is granted and the Trial Run is finished, disposal of the spent fuel can be started. First time in the world. IAEA Director General Rafael Mariano Grossi has stated that "Posiva's solution for the final disposal of spent nuclear fuel enables the sustainable production of nuclear electricity". Posiva and Finland is leading the way in the field.

REFERENCES

[1]. Fortum. Loviisan matala- ja keskiaktiivisen jätteen loppusijoituslaitoksen käyttölupahakemus (Operating license application for Loviisa's final disposal facility for low- and intermediate-level waste). Fortum Power and Heat Oy (2022).

[2]. Ministry of Economic Affairs and Employment, Finland. Management of spent nuclear fuel and radioactive waste in Finland, Second national programme under Article 12 of Directive 2011/70/EURATOM of the Council of the European Union. Publications of the Ministry of Economic Affairs and Employment, Energy 2022-20 (2022).

[3]. McEven, T. & Äikäs, T. The site selection process for a spent fuel repository in Finland – Summary report. Posiva report 2000-15 (2000).

[4]. Posiva. Operating licence application for spent nuclear fuel encapsulation and disposal facility. (2021)

[5]. Saanio, T., Kirkkomäki, T., Sacklén, N., Autio, J., Kukkola, T. & Raiko, H. Käytetyn ydinpolttoaineen loppusijoitustilat Olkiluodossa, Esisuunnitelma, vaihe 1. Työraportti 2003-74. Posiva Oy. (Spent nuclear waste repository at Olkiluoto, preliminary design, stage 1.) Working report 2003-74 (in Finnish). Posiva Oy (2003)

[6]. Saanio, T., Kirkkomäki, T., Keto, P., Kukkola, T. & Raiko, H. Preliminary design of the repository, stage 2. Working Report 2006-94. Posiva Oy (2006).

[7]. Saanio, T., Ikonen, A., Keto, P., Kirkkomäki, T., Kukkola, T. Nieminen, J. & Raiko, H. Outline design of the disposal facility 2009. Working report 2010-50. Posiva Oy (2009).

[8]. Saanio, T., Ikonen, A., Keto, P., Kirkkomäki, T., Kukkola, T., Nieminen, J. & Raiko, H. Design of the disposal facility 2012. Working report 2013-17. Posiva Oy (2013).

[9]. Posiva. Environmental Impact Assessment Report. (2008).■