SKB International Report 230

Strategy for managing low and intermediate level waste from a nuclear power plant in Estonia

Prepared for Fermi Energia OÜ, Estonia, by SKB International AB, Sweden

Final Report

December 2021

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Summary

Estonia is considering to introduce nuclear power for the production of electricity in so called Small Modular Reactors (SMR). Production of electricity in a nuclear power plant will also lead to the generation of radioactive waste, which will need to be taken care of in a safe way. This includes the spent nuclear fuel, which is highly radioactive, as well as different types of low and intermediate level radioactive waste. The latter is generated as process and maintenance waste during the operation of the nuclear reactor and as decommissioning waste during the dismantling of the reactor after the electricity production has been stopped.

In this report all aspects connected to the management of low- and intermediate level waste from a possible SMR in Estonia is described. This includes a description of the waste, how it is conditioned and packaged, and an overview of disposal methods in use worldwide. Further a discussion is given about the way to organise the responsibilities for the management of the waste and ensuring that financing is available.

Although the SMRs are different from the existing larger nuclear power reactors (NPP) in use, there are also many similarities. This means that a lot of information about the types of waste that will come from the SMRs can be gathered from the experience gained over more than 40 years of operation of large NPPs around the world, not least in Sweden and Finland.

According to the IAEA radioactive waste can be classified as high level, intermediate level, low level, very low level and exempt waste based on the requirements for long term isolation of the waste. The high level waste, which also includes the spent nuclear fuel, requires long term isolation at several hundred metres depth in stable bedrock, while exempt waste can be freely released from the NPPs. Very low level and low level waste can be disposed on or near the surface, while intermediate level waste requires deeper disposal.

Most of the low and intermediate level waste comes from the clean up of the reactor water during operation and from exchanged components and other waste during the maintenance of the reactors and later when the reactors are dismantled. The maintenance and dismantling also generates very low level waste. Before the waste leaves the NPP it is conditioned to be a solid product and packaged in suitable packages to ensure that radioactivity do not leak out from the packages during the subsequent handling. As the volumes of waste are small, about 50 m^3 per reactor and year, qualified packages can be used

Disposal facilities for low level waste are in operation in several countries since many years. Two different types are in use, engineered facilities built on or near the surface and subsequently covered with a tight capping and soil, or engineered facilities built in specially excavated rock caverns at 50 – 100 m depth or more.

In both cases multiple barriers are constructed against release of radioactive elements to the environment. Both types have been proven to be safe and fulfil the regulations of the country in question. The rock cavern disposal facilities, which are used e.g. in Sweden, Finland and Germany, are based on passive safety and built such that no active surveillance will be needed after closure of the facility. For the engineered facilities on the surface, which are used in e.g. France, Russia, and the USA, the safety is based on an active surveillance of the facilities during several hundred years, in particular the structural integrity and the drainage water from the facility. For longer times the safety is based on the passive barriers surrounding the waste.

Intermediate level waste, which is a smaller volume, requires disposal in rock caverns at greater depth. Until now only one disposal facility for intermediate level waste exists in the world, in the USA, while others are under construction, in Germany, or being designed, in France and Sweden.

According to an international convention, which Estonia has signed on to, it is a national responsibility to ensure the safe handling and disposal of all types of radioactive waste

generated in the country. The way the State fulfils this responsibility is organised differently in different countries. The responsibility for the on-site management of the waste always rests with the site licence holder. In some countries, e.g. France and Russian Federation, the State takes over the responsibility for developing, building and operating the disposal facilities, while in other countries, e.g. Sweden and Finland, this responsibility is put on the waste producers, i.e. the NPP owners. In any case the State always has the regulatory oversight and takes on the long term responsibility for closed disposal facilities.

Many of the activities connected to the management and disposal of radioactive waste will continue several decades after the NPPs have stopped producing electricity and generating an income. This is particularly the case for the management and disposal of the spent nuclear fuel, the decommissioning of the reactors and the disposal of the decommissioning waste. To ensure that financing is available for these activities funding systems based on the “polluter pays principle” have been developed in practically all countries having NPPs. Most often the funds are successively built up from a fee levied on the nuclear power production. This also ensures that the cost for the nuclear electricity takes into account all costs connected to the production. Examples of funding systems are discussed in the report.

Based on the description given in the report of different approaches to radioactive waste management and disposal, organization of responsibilities and funding, different options for Estonia are analysed and recommendations are given taking particularly the Swedish and Finnish experiences into account. It is proposed that the responsibility for the management and disposal is fully put on the company/companies owning the NPPs. It is further proposed that activities to find a suitable site for a disposal facility for low level waste starts by investigating the neighbourhood of the NPPs. The work on disposal of the intermediate level waste, which mainly is generated during the decommissioning of the reactors should preferably be coordinated with the corresponding work for the spent nuclear fuel. Further it is proposed that a funding system for the management of all types of radioactive waste, including the spent nuclear fuel, and for the decommissioning and dismantling of the reactors is established.

Extended summary

Introduction

Estonia is considering to introduce nuclear power for the production of electricity. Given the size of the electrical grid in Estonia and the expected needs for electricity, so called Small Modular Reactors (SMR) are of prime interest. Four types of reactors are primarily being considered, three of them being Light Water Reactors (LWRs) and one being a Gas Cooled Reactor (GCR).

Irrespective of choice of reactor type, radioactive waste will be generated and needs to be taken care of in a safe way. This includes the spent nuclear fuel, which is highly radioactive, as well as different types of low and intermediate level radioactive waste. The latter are generated as process and maintenance waste during the operation of the nuclear reactor and as decommissioning waste during the dismantling of the reactor after the electricity production has been stopped.

Although the SMRs are different from the existing larger nuclear power reactors (NPP) in use, there are also many similarities. This means that a lot of information about the types of waste that will come from the SMRs can be gathered from the experience gained over more than 40 years of operation of large NPPs around the world, not least in Sweden and Finland.

Fermi Energia OÜ has commissioned SKB International (SKBI) to prepare a study of all aspects connected to the management of low- and intermediate level waste from a possible SMR in Estonia. The management of the spent nuclear fuel is not included in this report.

Waste sources

Radioactive waste is generated during the production of electricity in a nuclear power reactor and needs to be taken care of in a safe and secure way. Most of the radioactivity is generated in the fuel and stays in the spent nuclear fuel. Some radioactive elements are also produced by irradiation of corrosion products in the reactor cooling water or leaked from the fuel to the water. The cooling water is constantly cleaned and the radioactive elements are collected in filters or ion exchange resins. Through the cooling water these elements are also contaminating other parts of the reactor. The filters, ion exchange resins, exchanged components, and material from the maintenance of the reactors constitute the low and intermediate level waste from the operation of the NPPs. When the reactors are decommissioned and dismantled some of the components will also be low-and intermediate level waste.

The radioactivity generated in the nuclear fuel consists of fission products and so called transuranic elements. As long as the nuclear fuel cladding remains intact these radioactive elements stay in the fuel. Experience shows that only a very small fraction of them is released to the reactor cooling water and end up in the low and intermediate level waste. Another source of radioactivity is activation products, which are created by neutron irradiation of structural materials in the fuel or the internals of the reactor pressure vessel and in material circulating in the reactor water or gas. Most of the activation products will end up in the intermediate level waste emanating from the decommissioning of the reactors.

Most of the radioactive substances have fairly short life, they disappear in minutes or days, while others could have longer life, of the order years to hundreds of thousands of years. Waste containing such radionuclides with longer life will have to be taken properly care of and disposed of in dedicated disposal facilities either on the surface or deep underground depending on the content of long-lived radioactivity.

Waste classification

Material which is classified as radioactive waste covers a wide range of radioactivity concentration, from material that can be freely released after careful measurements, with less than 1 Bq/g, to the spent fuel and high level waste, which can only be handled with very strong shielding and also needs cooling, and which contains 10^{10} Bq/g. It is thus practical to use a classification system for the waste, which takes into account the activity concentration and the life length of the radioactivity, which determines the requirements for disposal. The IAEA has developed a classification system with the following classes: exempt waste (EW), very short lived waste (VSLW), very low level waste (VLLW), low level waste (LLW), intermediate level waste (ILW) and high level waste (HLW)[1]. The disposal requirements for these classes are schematically shown in Figure E-1, ranging from simple disposal on the surface for VLLW to disposal in a geologically stable formation at several hundred meters depth for HLW. The spent nuclear fuel (SNF), if classified as waste, is an example of HLW. The activity boundaries between the different classes are not defined by the IAEA. They will depend on the specific design of the disposal facility used for a certain class of waste and the corresponding waste acceptance criteria (WAC) for that facility.

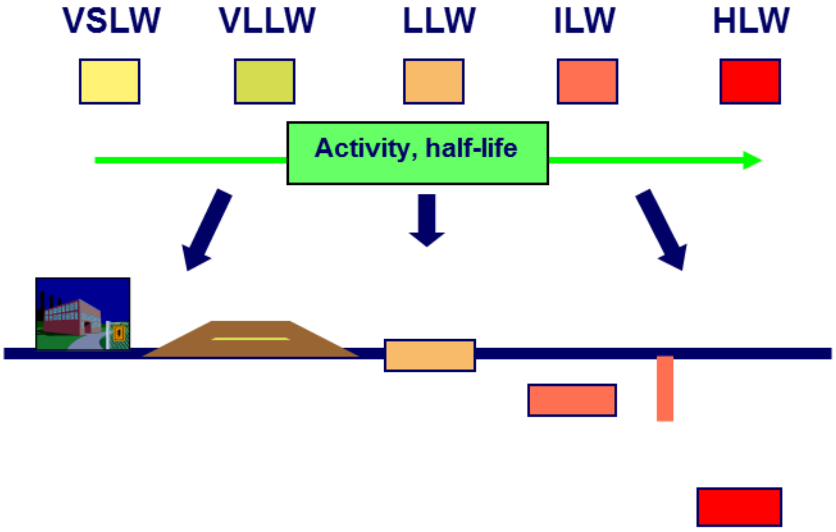

Figure E-1. Relation between waste classification according to the IAEA and disposal depth.

Management routes for low and intermediate level waste

As management and disposal of radioactive waste is complicated and costly and also gives radiation doses to the personnel handling the waste and potentially to other third parties, the amount of waste to be handled should be minimised. The most important step in the minimisation is to prevent that waste is generated, e.g. by avoiding bringing packaging material into the reactor building. Other steps include reuse of components after cleaning and recycling of scrap material.

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[1] The existing Estonian waste classification system is slightly different [Estonia,2017]. The main difference is that the distinction between low level waste and intermediate level waste is based on radiation dose and not on content of long-lived radioactivity. In this report the IAEA classification system is used.

For the radioactive waste that anyhow is generated the following handling steps can be distinguished:

- Sorting to avoid mixing of waste of different classes
- Treatment to reduce the waste volume
- Conditioning and packaging to get solid packages
- Storage if necessary, and transport to
- Disposal.

Ideally, the full chain from waste generation to disposal, should be optimised taking costs, doses to personnel, waste volumes to be disposed, and required disposal concept into account. In reality one or several of the steps in the chain have often been decided before all steps are available, making optimisation more difficult. In most cases world-wide, the treatment, conditioning and packaging have been decided when the NPP was built, and the disposal facilities, which have been built later, have had to be adapted to the existing waste. Now, in Estonia, when the introduction of nuclear power is at an early planning stage, there is a possibility to consider all steps in parallel.

Treatment, conditioning and packaging of different waste streams

Waste from reactor operation

In addition to the SNF several different types of waste are generated during the operation of a NPP. Most of this waste is VLLW or LLW.

The most important operational wastes are:

- Process waste from water or gas clean-up systems
- Solid maintenance waste from exchanged components, and
- Secondary waste from maintenance activities

The solid waste and secondary waste will be similar if it comes from a LWR or a GCR, while the process waste will differ, the main difference being that no water clean up system is used in the primary circuit of a GCR, only gas filters. In the following mainly waste from LWRs is described.

The treatment and conditioning of the waste will have to be adapted to the characteristics of the waste and the final disposal method. A flow diagram for different waste is shown in Figure E-2.

The most active LLW emanates from the clean-up systems in the reactor itself, where the circulating reactor cooling water is going through mechanical filters and ion exchange resins to ensure that the water passing through the reactor is very clean. The mechanical filters are solid bodies and is normally packaged directly in suitable packages and surrounded by concrete. The ion exchange resins are small plastic balls (they look like caviar). When they are no longer effective they are removed and solidified in suitable packages. The most frequent solidification method is by cementation. In some places, both in Sweden and Finland, also drying and solidification in bitumen is used. Also solidification systems using polymers are in use. More modern treatment methods, e.g pyrolysis, exist but are not widely used. Some resins with lower activity concentration can be dried and packaged without solidification.

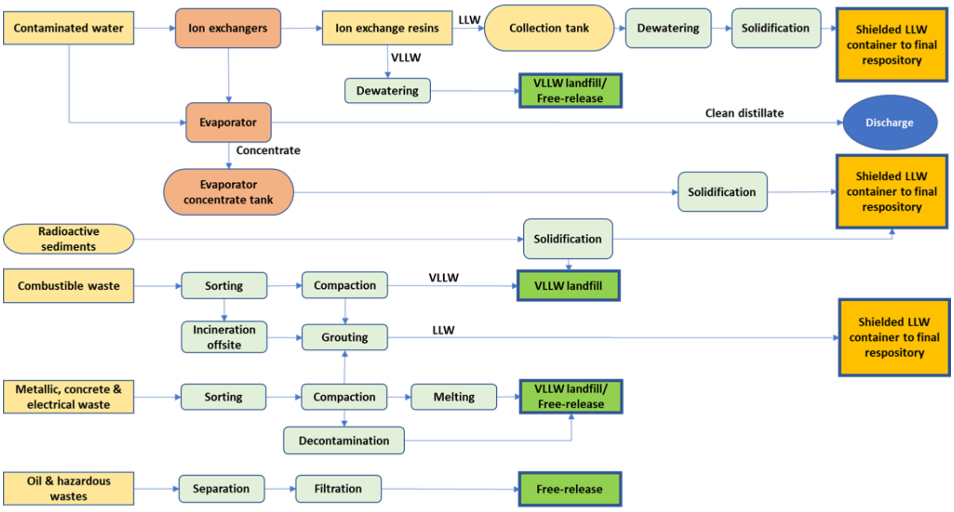

Figure E-2. Example flow diagram for typical waste streams from a LWR

Another product from water clean-up is so called condensate, which remains after evaporating the waste water to reduce the volume. The condensate is solidified in a similar way as the ion exchange resins.

The packages used for the solidified products are either cylindrical drums in steel or concrete or concrete cubes. The solidification and packaging limits the risk of release of radioactive particles. Some packages provide shielding such that packages can be handled without extra shielding, while others will need a shielding overpack during handling or even a remote handling. Further the packages are clean on the outside so that they can be safely handled.

Exchanged components will as much as possible be repaired and reused to avoid generation of waste that needs disposal. They are also cleaned (decontaminated) and the cleaning water is taken care of by evaporation as described above. Components that will go to waste will be packaged in similar packages as those described above. In some cases even larger packages can be used up to standard sea shipping containers for VLLW.

Figure E-3. Packages for LLW and VLLW used in Sweden

During maintenance several different types of waste appear ranging from paper towels, rags, and clothing to discarded equipment. Often this waste is compacted in a heavy duty press and packaged in the standard packages.

The volumes of LLW generated from a 300 MWe reactor can be estimated to about 50 m^3/year packaged waste. Thus, from operation of 4 reactors of this size under 60 years about 12 000 m^3 will be generated, half of it probably being VLLW.

As stated above no ILW is expected to be generated as process waste. However, some ILW, mainly control rods and other components close to the reactor core, can be expected to be exchanged during the operational life of the reactor. The radiation level of these components is high but the volumes are small and they are normally stored together with the fuel for later treatment and conditioning in connection with the decommissioning of the reactors.

Waste from decommissioning

During the decommissioning of LWRs essentially four types of radioactive waste will need to be taken care of for disposal:

- The reactor pressure vessel and its internals, including control rods and core structures. These are activated by neutron irradiation and strongly radiating.
- Solid waste from components that have been in contact with reactor water or gas systems.
- Irradiated or contaminated concrete from close to the reactor pressure vessel or from areas where water has been spilled on the floor.
- Secondary waste from the decommissioning activities, including from decontamination.

The first category is normally classified as ILW. Waste belonging to the other three categories are normally either LLW or VLLW. After treatment the LLW and VLLW can be packaged in similar packages that have been used for operational waste, or if it is found rational in larger packages, which require less cutting. Again, the possibility for optimization should be utilised.

The total volume of packaged decommissioning waste for a 1200 MWe LWR is about 4 000 m^3. Given that the waste volume per MWe probably is larger for a small reactor the total volume of VLLW and LLW from decommissioning the 4 SMRs can be estimated to 7 000 m^3

The volumes of ILW from decommissioning can be estimated to 600 m^3 for a 1200 MWe LWR, or about 1 000 m^3 four 4 SMRs.

For a GCR the decommissioning is more complicated than for an LWR. In particular the graphite surrounding the fuel will cause concern. Today, there is no accepted disposal route for irradiated graphite available in the world. Studies are underway for Russian, French and UK reactors with graphite cores.

Volumes of radioactive waste which will need disposal

In summary the waste volumes from 4 SMRs are:

7 000 m^3 VLLW
11 000 m^3 LLW
1 000 m^3 ILW

Storage and transport of low- and intermediate level waste

After the different types of waste have been conditioned and packaged there is normally a need for a period of storage, either awaiting the availability of a suitable disposal facility or buffering to be able to have an effective disposal campaign. The storage facilities for LLW and ILW are normally quite sturdy concrete buildings with shielding walls to avoid restrictions on the outside due to radiation. The equipment used in the stores will depend on the highest radiation level of the waste packages. The equipment can range from using simple forklift trucks for low radiation packages to fully remote handling with cranes for packages with higher radiation level. The size of the storage facilities will depend on what buffer capacity is needed before disposal. It can range from a year's production or so, if a disposal facility is available, to the full operation time for the NPPs if it is decided to only start disposing in connection with the decommissioning of the reactors.

Figure E-4. Handling of waste packages in storage facility at Ringhals NPP.

Depending on the location of the disposal facility different types of transports will be necessary. If the disposal facility is built at or close to the NPP premises the transports can be fairly simple taking one package at a time. If needed some of the transports can use radiation shielding. If the disposal facility is located at a separate place, which requires transports on public roads or rails or by the sea the requirements are more stringent. The transports must follow the international transport recommendations issued by the IAEA. For LLW normally so called strong industrial packages can be used, which are providing adequate radiation shielding and which have to be sturdy enough to survive certain prescribed accidents without leakage of the radioactivity. Some ILW transports will require stronger packages, so called Type B packages. Transports of LLW and ILW have been performed for 50+ years in different countries around the world using road, rail and sea transports.

Disposal of low and intermediate level waste

Low level waste

According to the IAEA classification scheme:

> LLW is waste with only limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in near surface facilities.

LLW has been disposed in several countries since more than 40 years. In the early years the waste was disposed in simple trenches. This approach is no longer acceptable, and some waste disposed in this way has been retrieved. Today, two types of disposal facilities are used for LLW:

- Engineered facilities built on or near the surface and subsequently covered with a tight capping and soil, or
- Engineered facilities built in specially excavated rock caverns at 50 – 100 m depth or more.

In both cases multiple barriers are constructed against release of radioactive elements to the environment. Both types have been proven to be safe and fulfil the regulations of the country in question. The rock cavern disposal facilities are based on passive safety and built such that no active surveillance will be needed after closure of the facility. For the engineered facilities on the surface the safety is based on an active surveillance of the facilities during several hundred years, in particular the structural integrity and the drainage water from the facility. For longer times the safety is based on the passive barriers surrounding the waste.

Engineered disposal facilities on the surface are the most common and are used, e.g. in France, the USA and the Russian Federation. As an example the French facility, Centre de l'Aube, is described in the report. It consists of a series of thick walled concrete compartments (houses), about 25 by 25 m wide and 8 m high. In these the waste is stacked and surrounded by concrete grout. When they are full a concrete lid is put on the top, and then a geomembrane and a couple of meters of clay, soil and gravel is put as a cap to cover the compartments. Under each compartment there is a drainage system for control of water leakage. A view of the Centre de l'Aube, which is a very large disposal facility is shown in Figure E-5. So far no final capping has been applied on this picture. For Estonia about 8 compartments will be needed (see ring on the picture).

Figure E-5. Aerial view of the Centre de l'Aube disposal facility for low-level waste in France (Courtesy of Andra). The red ring corresponds to the size needed for Estonia.

Disposal facilities with engineered structures in rock caverns are in operation in Sweden, Finland and Hungary and are planned in several other countries. In Sweden and Finland they are built in crystalline rock, while in other countries other geological media are considered.

The Swedish SFR facility, which is located close to the NPP at Forsmark, consists of a series of rock chambers with different engineered structures adapted to the different types of radioactive waste generated in Sweden and their corresponding activity content. The most active LLW is disposed in a concrete silo, about 25 m in diameter and 50 m high, where the waste is stacked and surrounded by concrete grout. Between the concrete wall and the rock bentonite clay is put to ensure tightness. Less active waste is placed in horizontal rock chambers. In some cases, the waste is surrounded by a concrete building, in other just put in on the floor. A schematic presentation of the SFR is shown in Figure E-6. A similar design, but only with silos, is used at the Olkiluoto NPP in Finland.

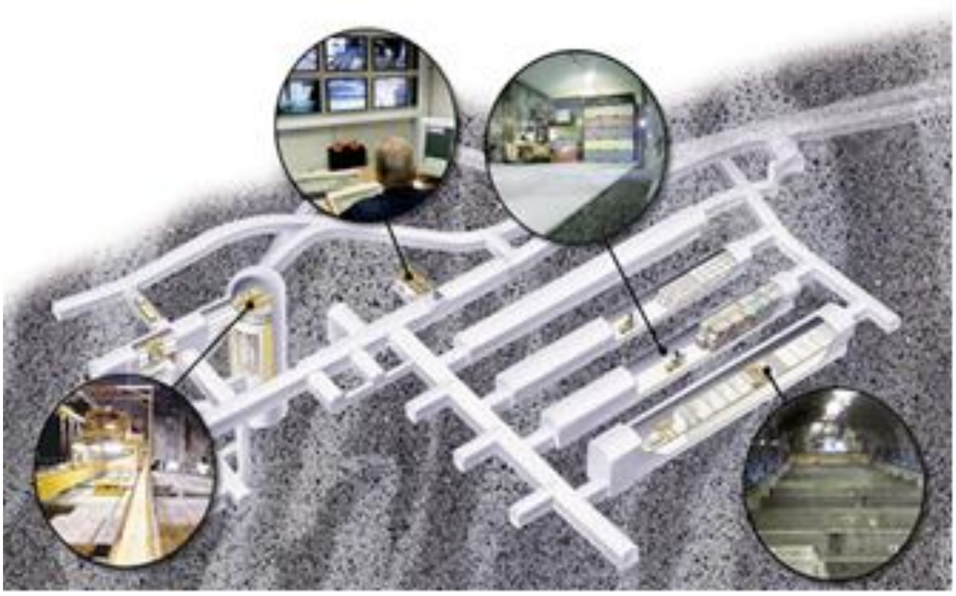

Figure E-6. Schematic presentation of the SFR disposal facility for LLW in Sweden. On the left a silo for the most active waste and on the right rock chambers for less active waste.

In most countries a central disposal facility for the whole country or a large region is being used. In Finland, however, separate disposal facilities have been built at each of the two NPP sites. This has the advantage of avoiding transports on public roads or sea and has also provided an opportunity for optimising the disposal activities and integrating them as part of the normal operation of the NPPs.

Very low level waste

In some countries simpler surface disposal arrangements are made for VLLW, i.e. waste with such a low activity content that it does not need a high level of containment and isolation and could almost be released freely. This is used at some of the NPPs in Sweden and is planned at Olkiluoto in Finland.

Intermediate level waste

According to the IAEA classification scheme:

> ILW is waste that, because of its content, particularly of long lived radionuclides, requires disposal at greater depths, of the order of tens of meters to a few hundred metres.

At present only one disposal facility for ILW is in operation in the world, the WIPP facility in salt rock in the USA. Other facilities are under study in France in clay, in Germany in a former iron mine and in Sweden in crystalline rock. The design could be similar to SFR but at greater depth.

Organizational structure for management of radioactive waste

In accordance with the Joint Convention on the safety of spent fuel management and the safety of radioactive waste management it is a national responsibility to ensure the safe handling and disposal of all types of spent fuel and radioactive waste generated in the country. The way the State fulfils this responsibility is organised differently in different countries. The responsibility for the on-site management of the waste always rests with the site licence holder. For the next steps storage, transport and disposal essentially three different approaches can be noted:

- The State takes the full responsibility to develop, build, operate and close all disposal facilities needed in the country. Normally this is done through a special State controlled organisation. This is e.g. the case in France, where Andra is responsible for disposal of all types of radioactive waste.
- The State takes responsibility for disposal of SNF, HLW and ILW, while the disposal of LLW is the responsibility of the waste producers, the NPP owners, often through a dedicated disposal company. This is the case in the USA, where US Department of Energy is responsible for the SNF, HLW and ILW, while commercial companies dispose of LLW.
- The full responsibility for management and disposal of all types of waste rests with the waste producers. This is e.g. the case in Sweden and Finland with the specialised companies SKB and Posiva fully owned by the waste producers.

Irrespective of which organisational form is used, the State always have the final oversight through an independent nuclear regulator. The State will also have to take the long term responsibility of any disposal facility some time after closure.

In all countries, irrespective of how the responsibilities are allocated, a special waste management organisation (WMO) is set up to plan and implement the disposal facilities, in particular for the management of the SNF and ILW, but also often for the disposal of LLW. Examples are SKB in Sweden, Posiva in Finland, RATA in Lithuania, BGE in Germany, and Andra in France.

There are advantages and disadvantages of the different approaches. The third approach, which is used in Finland and Sweden, where the waste producers have the full responsibility for the waste up to and including disposal, has the advantage that the organisations, which are dependent on that the waste they produce will be taken care of, are in control of all the steps and can ensure that the system can be optimised, and the necessary facilities are available in time. They will also be in control of the costs, which they anyhow will have to cover.

The first approach, where the State takes the full responsibility, has the advantage that the waste producers, i.e. the NPPs, can concentrate their activities on their prime business, i.e. to produce electricity. It is also seen in some countries as a guarantee that the disposal is made in a safe way without any technical shortcuts.

Financing and funding radioactive waste disposal

The time schedule for many activities connected to management of SNF and radioactive waste is long and activities will continue several decades after the NPPs have stopped producing electricity and generating an income. This is particularly the case for the management and disposal of the SNF, and for the decommissioning of the reactors and disposal of the decommissioning waste. To ensure that financing is available for these activities funding systems based on the “polluter pays principle” have been developed in practically all countries having NPPs. Most often the funds are successively built up from a fee levied on the nuclear power production. This also ensures that the cost for the nuclear electricity takes into account all costs connected to the production.

The specific funding system differs between countries, e.g. what should be covered by the funding. In some countries disposal of all types of waste is covered by one fund, while the costs for decommissioning the reactors is covered by another fund. In other countries this is put together in one single fund. In some countries only costs appearing after the power production has been stopped is covered by the funding, while in others also the earlier costs are included, e.g. for research and development or storage. In the first case the early costs are covered directly as operational costs as they appear. In several countries this is the case for disposal of LLW.

The funds normally generates an interest to ensure that they at least follow the inflation in the country. In some countries the funds have just been part of the normal State budget, which has created problems with ensuring their value when needed.

In most cases the funds are under control of the State to ensure their availability when the financing is needed. Irrespective of this, in several countries the waste producers remain responsible for ensuring that adequate funding is available. This is e.g. the case in Sweden, Finland and France. In other countries the waste producers pay a one time fee to the Waste Management Organization to cover all their future costs.

The level of the fees varies between the countries but is typically of the order of a few tenth of a Eurocent per kWh generated by nuclear electricity. In this way quite large funds have been built up. In Sweden e.g. the fee at present is around 0,5 Eurocent/kWh and the actual value of the fund is 7.5 billion Euros, although already more about 4 billion Euros has been spent on research and development for SNF disposal and on building and operating an interim storage facility for SNF and a transport system. The funding needed for disposal of LLW is at least an order of magnitude lower.

Recommendations for Fermi Energia OÜ and Estonia

The situation in Estonia is particular as no NPP has yet been built. Thus, this study provides a background for the planning of the new SMRs being considered for operation in 2035 and later.

A key finding of the study is that it is advantageous to consider the management and disposal of all types of waste to be generated already at the planning stage. This provides a possibility to design the treatment and conditioning methods in such a way that the whole system from generation to disposal can be optimised. This is particularly the case for LLW. It is thus important to consider possible options for the design and location of a disposal for LLW at an early stage.

In this study primarily the management of radioactive waste from the NPPs planned to be built in Estonia is considered. Based on the presentations of international experience, especially from Sweden and Finland, given in this report the following recommendations can be given for the management of LLW:

- The responsibility for management and disposal of LLW should rest with the owners of the NPP.
- In connection with the siting of the NPPs, geological investigations should be performed concerning the possibilities to also build a safe disposal facility for LLW at the same premises or close to it.
- In parallel alternative possibilities should be studied as this will be needed for the Environmental Impact Assessment
- The choice between an underground rock cavern disposal or an engineered surface disposal will be based on the geological conditions on site and also take into account economic, political and public acceptance aspects.

- The required capacity will be about 15 – 25 000 m^3. About 30 % of it will come from the decommissioning of the reactors.
- The disposal facility should preferably be operational within a few years after the start of operation of the first NPP. As the waste generation will span at least 80 years it might be advantageous to expand the disposal capacity in steps.
- It might also be advantageous to consider installing a simple disposal facility for VLLW on the site, as this will reduce the disposal volume needed for LLW and could simplify the treatment and conditioning methods at the NPPs.
- The choice of methods for treatment and conditioning of the radioactive waste from NPP operation should be based on the most modern technologies available, taking operational experiences, operational doses and long term safety in the disposal facility, as well as the costs into account. In particular, the compatibility between the waste and the disposal must be ensured.
- If no suitable site for a LLW disposal facility can be found at or close to the NPP site a wider search in Estonia will be required. This will involve considerable geotechnical, environmental, industrial, sociological and public acceptance activities as has been the case for the siting of the disposal facilities for SNF in Sweden and Finland.
- In this case the organisational structure might be different and the task could be given to a separate waste management organization (WMO), which also would be responsible for management and disposal of SNF and ILW.
- Based on the experiences in Sweden and Finland it could be efficient if the WMO is a daughter company of the NPP owner(s) or a direct part of the owner company, thus leaving the full responsibility with the NPP owners OÜ. The decision whether the WMO should be a State controlled organization or belong to the power company, however, is in the end a political decision to be taken in Estonia.
- The costs for disposal of the operational waste could be covered directly by the operational income from power production. A funding system will be needed for disposal of the decommissioning waste. This could preferably be coordinated with the funding system for SNF management and NPP decommissioning. Based on international experience the funding should be covered by a fee on the electricity production. The organisation of the funding system will need further considerations taking the specific Estonian circumstances into account.

The situation for the ILW, which will require deeper disposal, is slightly different as most of this waste will be generated during the dismantling of the nuclear power plants. It might thus be advantageous to consider the disposal of ILW in connection with the disposal of SNF. This will require that some ILW from the operation of the NPPs and the existing ILW from earlier Soviet practices will have to be stored. These volumes are, however, small.

Abbreviations

A.L.A.R.A.	Estonian waste management organisation
Andra	French WMO. Agence Nationale pour la gestion des Dechets Radioactifs
BGE	BundesGesellschaft für Endlagerung
BWR	Boiling Water Reactor
Bq	Becquerel, Unit for radioactive decay, one disintegration per second
Cigéo	Centre industriel de stockage géologique, French disposal facility for HLW and LILW-LL
CSA	Centre de Stockage de l’Aube. French final repository for LILW-SL
DF	Decontamination Factor
EIA	Environmental Impact Assessment
Enresa	Spanish WMO. Empresa Nacional de Residuos Radiactivos, S.A. S.M.E., (Enresa)
EUR	Currency, European Euros
EW	Exempt Waste
FP	Fission Product
GCR	Gas Cooled Reactor
HLW	High Level radioactive Waste
HTGR	High Temperature Gas Cooled Reactor
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste (IAEA definition)
LLW	Low Level Waste (IAEA definition)
LMFBR	Liquid Metal Fast Breeder Reactor
LWR	Light Water Reactor
MW_e	Electric power, expressed in megawatt
MSR	Molten Salt Reactor
N/A	Not applicable
NPP	Nuclear Power Plant
OECD/NEA	Nuclear Energy Agency of the Organisation for Economic Cooperation and Development
Posiva	Finnish WMO
PWR	Pressurized Water Reactor
RATA	Lithuanian Radioactive Waste Management Agency WMO
R&D	Research and Development
RW	Radioactive Waste
SEK	Currency, Swedish Krona.

SFL	Swedish final repository for ILW
SFR	Swedish final repository for LLW at Forsmark
SKB	Swedish Nuclear Fuel and Waste Management Company
SKBI	SKB International
SMR	Small Modular Reactor
SNF	Spent Nuclear Fuel
SSM	Swedish Radiation Safety Authority
Sv	Sievert, unit for radiation dose
VLJ	LLW disposal facility at Olkiluoto, Finland
VLLW	Very Low Level Waste
VSLW	Very Short Lived Waste
WAC	Waste Acceptance Criteria
WIPP	Waste Isolation Pilot Plant
WMO	Waste Management Organisation

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1 Introduction – Scope and purpose of the study

1.1 Background

Estonia is considering to introduce nuclear power for the production of electricity. Given the size of the electrical grid in Estonia and the expected needs for electricity so called Small Modular Reactors (SMR) are of prime interest for Estonia. Several different types of SMRs are being developed in different countries. These include standard light water reactors (LWR) with improved safety features as well as innovative reactors, e.g. gas cooled reactors (GCR), liquid metal fast breeder reactors (LMFBR) and molten salt reactors (MSR). These are at different stages of development. In Estonia primarily four types of reactors are under consideration, three of them being LWRs and one being a GCR. Some details about these reactors are given in Annex 1.

Irrespective of choice of reactor type radioactive waste will be generated and needs to be taken care of in a safe way. This includes the spent nuclear fuel, which is highly radioactive, as well as different types of low and intermediate level radioactive waste (LLW and ILW). LLW and ILW are generated as process and maintenance waste during the operation of the nuclear reactor and as decommissioning waste during the dismantling of the reactor after the electricity production has been stopped. The types of waste generated from the SMRs are similar to the waste from the reactors already in operation around the world since several decades. This is particularly the case for the reactors based on LWR technology. During these more than 50 years of nuclear reactor experience a lot of efforts have been dedicated to reduce the volumes of waste and to improve the treatment and conditioning technologies. The volumes of waste from new modern reactors can thus be expected to be lower than for earlier reactors and the conditioned waste more suitable for final disposal.

The radioactive substances in the radioactive waste make it necessary to consider two aspects during the handling of the waste, the direct radiation from the waste and the risk for spreading of the radioactive substances. Due to the first aspect, direct radiation, most of the radioactive waste will need shielding during handling. To protect against the second aspect, spreading, the waste is solidified, encapsulated and/or contained in specific waste packages to avoid that the radioactive substances can reach man. In addition to the radioactivity also the possible chemical toxicity of the waste needs to be considered. The main steps of radioactive waste management are thus, sorting, treatment, conditioning, packaging, storage, transport and disposal.

Some of the radioactive substances will disappear through radioactive decay after a short time, hours or days, while some will remain dangerous for a longer period, several years up to hundreds of thousands of years. This is particularly important for the radioactivity in the spent nuclear fuel. Long term storage is thus not a management option and the waste will need disposal underground, where the geological setting in combination with the waste packages provide the required isolation against spreading.

The radioactive content of the low- and intermediate level waste is such that the waste needs to be taken care of and handled safely for several hundred years. This is achieved by disposing of the waste underground in rock caverns or in engineered disposal facilities on or just under the surface. In Sweden and Finland disposal in rock caverns is used.

1.2 Goal, scope and purpose

Fermi Energia OÜ has commissioned SKB International to prepare a study of all aspects connected to the management of low- and intermediate level waste from a possible SMR in Estonia.

The goal of the study is to develop a high-level qualitative strategy for safe cost-efficient and sustainable management of the different types of low and intermediate level waste, ranging from practically non-radioactive very low level waste to intermediate level waste with long-lived radionuclides. The waste will come from the operation and subsequent decommissioning of a nuclear power plant with up to 4 LWRs or GCRs with a total capacity of up to 1200 MWe capacity, which will be commissioned in Estonia between 2035 and 2050.

The study will describe and discuss advantages and disadvantages of alternative scenarios for managing the waste and identify the most feasible strategy or strategies, based on experiences in different countries around the world, in particular, but not limited to, Sweden and Finland. The assessment will consider different aspects such as safety, economy and sustainability and take into account the guiding principles in international standards and best practices. In addition to technical aspects also the responsibilities of the participants in radioactive waste management and the organization of the work, as well as the financing, will be discussed.

This study will not deal with the management of spent nuclear fuel or other high level waste.

The main purpose of the study is to serve as an input for public and private stakeholders, including authorities, for communicating Fermi Energia's long-term commitment to safely and efficiently managing nuclear waste. The results will be incorporated into Fermi Energia's general strategy for developing the nuclear power plant.

1.3 Structure of the report

The report is structured in a logical way. Following this introductory chapter there will seven chapters (2-8) describing the radioactive waste (RW) from a technical point of view and providing information about the approaches used in different countries to safely manage and dispos of RW. The following two chapters (9-10) provides information on the organization of the responsibilities and work to take care of the waste and how this is being financed. Finally the last chapter 11 provides conclusions and recommendations.

In chapter 2 the basic information and principles for managing RW waste ares given and the waste classification system is described. It also gives an overview of RW generated by a NPP.

Chapter 3 provides an overview of the management steps and routes for LLW and ILW.

Chapter 4 provides some more details of typical LLW and ILW generated in the type of reactors considered for Estonia, and in chapter 5 different methods for treatment, conditioning and packaging of LLW and ILW in different countries are provided.

Chapters 6 and 7 describes how LLW and ILW is stored at reactor sites and transported to disposal facilities.

In chapter 8 a rather detailed description is given of the different methods for disposal of LLW and ILW that are utilised in different countries. Also the disposal of VLLW is described. Recommendations are provided to Estonia.

Chapter 9 deals with the responsibilities of different actors involved in RW and based on experiences around the world recommendations are given how the responsibilities and work could be organised in Estonia.

In chapter 10 different methods for organising the future financing of all RW management activities. As some of the costs will appear after the electricity production has ceased different funding mechanisms are discussed.

Finally in chapter 11 the conclusions and recommendations are summarised.

2 Radioactive waste from nuclear power production – classification and principles

2.1 Introduction

The generation of radioactive waste (RW) is an unavoidable consequence of nuclear power production as well as of other applications of nuclear technologies, e.g. the use of radioactive substances in medicine or research. Some of the waste, in particular the spent nuclear fuel (SNF) and RW from processing of the SNF, is very dangerous and needs to be handled with great care and be isolated from human beings and the environment. These wastes will also remain dangerous for very long time periods, hundreds to hundreds of thousand years. Other RW with substantially lower radioactivity level are less hazardous, but still needs to be isolated for several hundred years. The end point of RW management is therefore in most cases disposal, either near the surface for short lived waste (a few hundred years) or at depth (500 - 1000 m) in geological formations for the SNF, high level waste (HLW) and other long lived waste (ILW).

2.2 Basic principles for radioactive waste management

To reduce the need for disposal one of the basic principles for RW management is to minimize the generation by waste avoidance, sorting, cleaning and volume reduction. Like for other waste in our society, RW should follow the principles of the "waste management hierarchy" (Figure 2.1), which shows the steps applied to reduce the volumes to be disposed to a minimum.

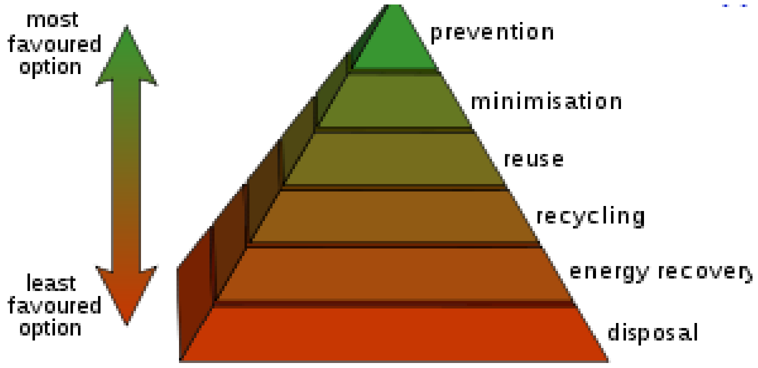

Figure 2.1. The waste management hierarchy to minimise the waste that will need disposal

At the highest level is the *prevention or avoidance* of waste generation. One such example is to remove the packaging of all material that is brought into an area of the reactor where it could be contaminated, and thus become RW.

At the next level comes *minimisation*, which is achieved by using the components as long as possible, *reusing* or decontaminating exchanged components and *recycling* material that has been declared waste, for instance by recycling scrap metal. For RW management, "*energy recovery*" is not generally applicable.

Finally RW that cannot be reused or recycled will need disposal. It is useful to separate the waste into different classes, depending on the content of radioactivity, and which can disposed of with different requirements on the long term containment. This is discussed in the next section.

The development of alternative routes to disposal requires efficient means in terms of treatment, decontamination and characterization. The separation into different classes requires efficient evaluation tools for optimization of the RW management.

Often the costs of disposal is a good driver to promote minimisation or recycling but sometimes the economic trade off can be difficult between direct disposal of the waste and treatment to reduce disposal volumes or to enable recycling. Ideally, the cost of treatment should be less than the cost of avoided disposal space, but also other criteria have to be considered such as radiation protection or public acceptance. These factors can weaken the advantage of waste minimisation because of doses to the workers during waste processing. The opportunity for recycling of materials from a nuclear facility can also be restricted or reduced because of opposition from the public, or fear of the industry to be associated with radioactivity.

2.3 Classification of radioactive waste

The IAEA defines RW as any waste that contains or is contaminated with radionuclides at concentrations or activities greater than clearance levels as established by a regulatory body [IAEA, 2007]. It is recognized that this definition is purely for legal and regulatory purposes and that material with activity concentrations less than clearance levels is also radioactive from a physics point of view.

RW covers a wide spectrum of material types, physical composition and radioactivity concentration. Also the composition of radionuclides included in the waste and their corresponding half-lives differs widely. This means that the methods to take care of the RW will have to be adapted to the specific waste form. The radiation level determines the handling and storage method for the waste and the concentration and half-life of the radionuclides determines the way they need to be finally disposed of. Radionuclides with half-lives shorter than 30 years are considered to be short lived.

The IAEA has defined a classification scheme that is based on the way the waste will be finally disposed of [IAEA, 2009a]. It has the following 6 classes of RW:

- **Exempt waste (EW):** Waste that meets the criteria for clearance, i.e. it has been cleared from regulatory control, it is not considered RW;
- **Very short lived waste (VSLW):** Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared for uncontrolled disposal, use or discharge;
- **Very low level waste (VLLW):** Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control;
- **Low level waste (LLW):** RW with only limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities;
- **Intermediate level waste (ILW):** Waste that, because of its content, particularly of long lived radionuclides, requires disposal at greater depths, of the order of tens of meters to a few hundred metres;
- **High level waste (HLW):** Waste with levels of activity concentration high enough to generate significant quantities of heat or waste with large amounts of long lived radionuclides. Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal of HLW. SNF, if considered waste, is a HLW.

The waste classification is shown schematically in Figure 2-2 and 2-3. There are no strict limits between the different waste classes. Instead, the limits, which might differ from country to country, are determined by the disposal routes chosen in a specific country and the corresponding safety assessment. A specific disposal route can accommodate a certain amount of different radionuclides. If the disposal route is landfill, the waste is classified as VLLW, if it is disposal in near surface facilities it is LLW, and if the disposal route is at intermediate level depth the waste is ILW.

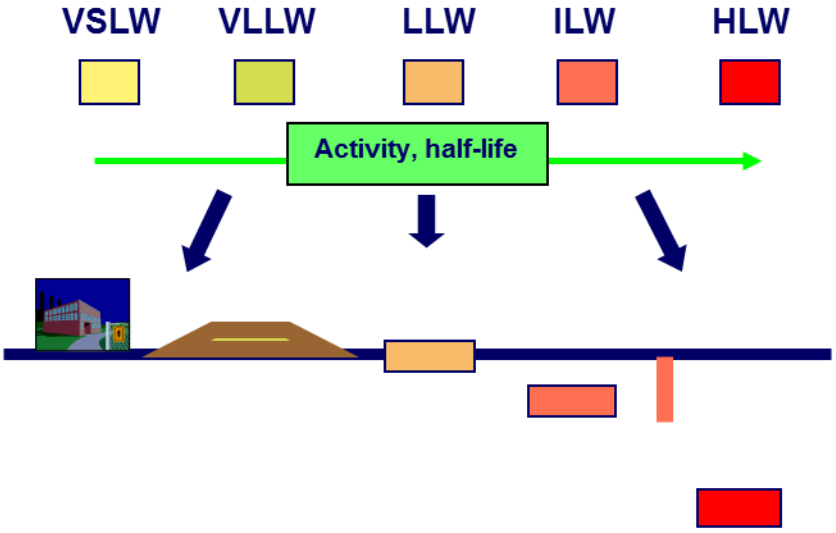

Figure 2-2. Relation between waste classification and disposal depth.

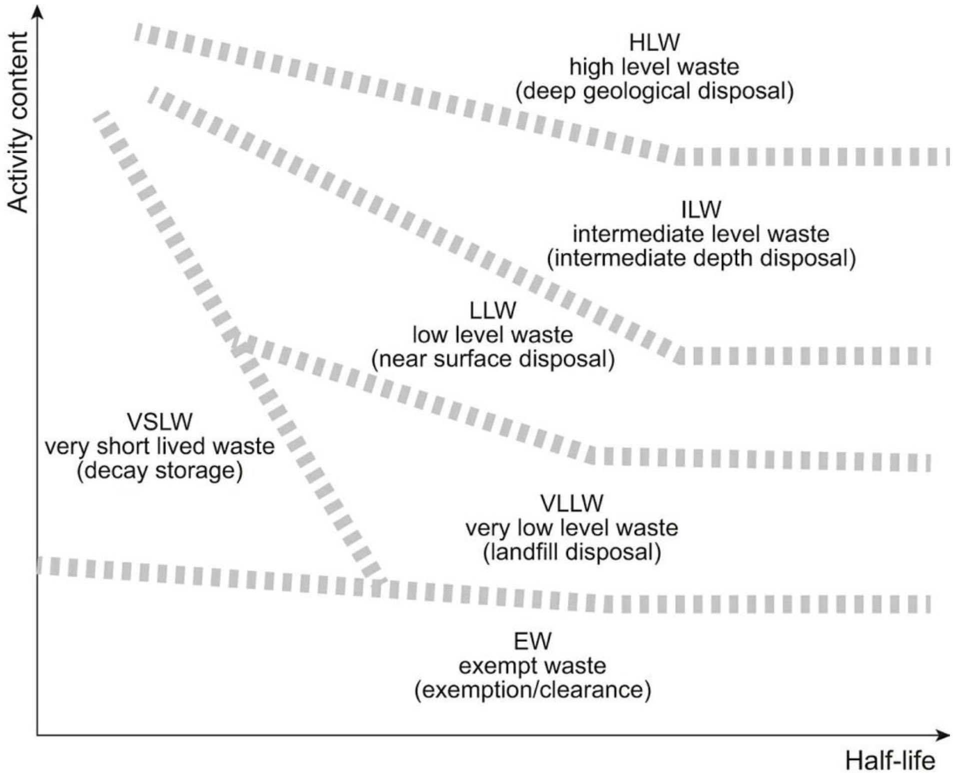

Figure 2-3. Conceptual illustration of the waste classification system. [IAEA, 2009a]

This IAEA classification scheme is not used in all countries. In many countries earlier classification schemes are still in use, which sometimes lead to confusion, especially the definition of low level waste and intermediate level waste. In many countries, including Sweden and Finland, the term low level waste is purely used for waste packages, which will not require shielding during handling, while LLW packages, which require shielding are called intermediate level, although the content of long-lived radioactivity is such that it will not require disposal at depth. In Sweden and Finland this short lived low- and intermediate level waste, which according to the IAEA classification is called LLW, is disposed in one near surface rock facility, while the long lived ILW will be disposed later at greater depth.

A similar classification is also used in Estonia [Estonia, 2017]. In this report, however, we will be using the IAEA definition of LLW and ILW.

The VLLW class is so far only used as a distinct classification in a small, but increasing, number of countries (e.g. France, Finland, Japan, Lithuania, Spain and Sweden). In most other country classification schemes, it is included as part of the LLW stream. The main source of VLLW comes from the maintenance of nuclear reactors and from the subsequent decommissioning and dismantling. Some of this waste might in reality be EW but the requirements to measure and classify the waste as such are so strict that it is more efficient to classify it as VLLW. Normally the VLLW can be handled without shielding.

The main source of LLW is process waste from the operation of the nuclear reactors, nuclear fuel cycle facilities and nuclear research facilities, and from the maintenance of these facilities. Important quantities of LLW will also come from the future decommissioning and dismantling of idle reactors after the power production has been finally stopped. Much of the LLW can be handled without special shielding, while a certain part, in particular the material used for clean-up of the process water during reactor operation, will need both solidification and shielding.

The main source of ILW is material that has been irradiated by neutrons in the reactor, or which have been generated during the management of the SNF. This is particularly the case if the SNF is reprocessed before disposal.

In addition to classifying the waste according to radioactivity content it is also important to distinguish between solid, liquid and gaseous waste, as well as to consider the radiation level at the waste package. The physical form of the waste (solid, liquid or gaseous) determines the treatment, conditioning and packaging methods to be used for the waste. Also the possible content of toxic chemicals needs consideration.

2.4 Radioactive waste from nuclear power production

2.4.1 Sources of radioactivity

In a nuclear power plant there are two sources for the production of radioactive substances, the fission by neutrons and absorption of neutrons taking place in the fuel itself, and the irradiation of material in the reactor that is exposed to the neutrons from the fission process (activation).

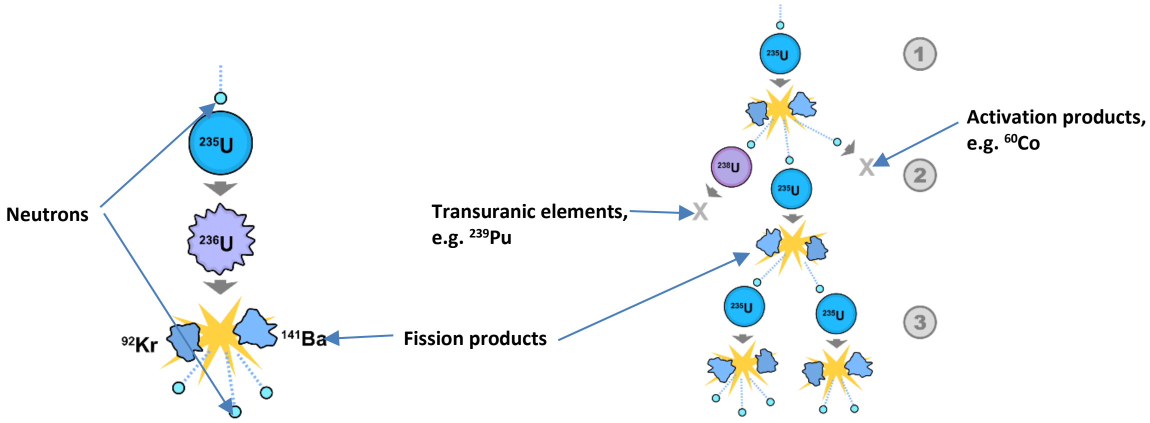

Figure 2-4. Creation of radioactive substances during the fission process.
In the fission process two lighter nuclides, fission products, are formed and 2-3 neutrons are released (left figure).
These neutrons are used for a new fission, but also absorbed in U-238 to form transuranic elements or in construction material to form activation products (right figure).

The radioactive substances produced from the first source are fission products and transuranic elements (elements heavier than uranium). The fission products are the lighter elements (e.g. cesium, strontium and iodine) that are created when the heavier atoms (e.g. uranium or plutonium) are split (fissioned) and energy is released (See left side of Figure 2-4). The transuranic elements (e.g. plutonium, americium and curium) are generated by the absorption of neutrons in uranium and the successively created transuranic elements (Right side of Figure 2-4). The amount of fission products and transuranic elements is directly coupled to the energy that has been generated.

The fission products and transuranic elements are kept in the fuel and contained by the fuel cladding. It will only be released to other parts of a nuclear power plant if the fuel cladding is damaged. Minor amounts could also emanate from fuel contamination on the outside of the fuel cladding that remains after the fuel fabrication.

The SNF is highly radioactive and will need shielding and cooling for the subsequent handling. The most important radionuclides in the SNF are the fission products Strontium-90 and Cesium-137, both with a half life[2] of 30 years: The most important transuranic elements are different isotopes of Plutonium, Americium and Curium., with half lifes between 14 and 370 000 years.

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[2] The half life of a radioactive substance is the time it takes for the radioactivity to decrease by 50%. To decrease a factor 1000 takes 10 half lives.

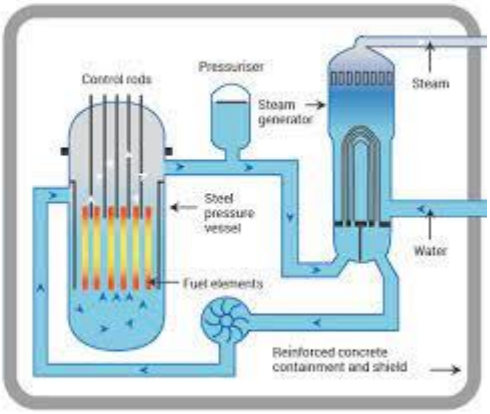

Figure 2-5. Schematic view of a PWR nuclear reactor and its primary cooling circuit with the coolant passing through the reactor core.

The second source of radioactive substances in a reactor, activation products, is the result of irradiation of material in the reactor by neutrons from the fission process (See right side of Figure 2-4). Only material in and inside the reactor pressure vessel and in the concrete that immediately surrounds it will be exposed to sufficient neutron fields for activation. The highest activity will be generated in the core components holding the fuel and in other internal parts surrounding the core in the pressure vessel.

Also, material contained in the cooling water, which passes through the reactor core could become activated (See Figure 2-5). This could be metal ions or particles from corrosion in the primary circuit of the reactor or other trace elements contained in the coolant or coolant moderator. The most important activation products are Cobolt-60 and Nickel-63, with half lives between 5 and 100 years.

Radioactive substances thus created in the reactor water or leaked out from the fuel to the reactor water could then be transported through the primary system of the reactor and contaminate surfaces and filters, thus creating a radiation field around these components and in the end creating a radioactive waste. This is the main source of LLW from nuclear power production. To minimize the creation of activation products one strives to keep the primary circuit water very clean through ion exchange and mechanical filtering as well to reduce the corrosion by adjusting the chemical environment, e.g. by adding lithium hydroxide or hydrazine to the coolant. Also gaseous radioactive fission and activation products are formed and transported by the coolant and coolant-moderator to a degasification system.

In a GCR the activation products are transported in the gas coolant and removed by mechanical filtering.

2.4.2 Radioactive waste from nuclear power production

Several kinds of RW are generated from nuclear power production. The most hazardous is the SNF (if it considered as waste), or the HLW from chemical reprocessing of the SNF. ILW is mainly irradiated core components and some long lived waste from reprocessing. LLW comes from the treatment of the water in the reactor primary circuit and fuel handling facilities (process waste) and from components and material that have been in contact with such water (technological or maintenance waste). Some of this waste could even qualify as VLLW. LLW and VLLW are generated both during the operation and maintenance of the nuclear power plants and during their final decommissioning after the power production has ceased. In particular, large volumes of VLLW are generated during the dismantling.

Some examples of different types of waste is given in Figure 2-6. It can be seen that the activity level of the waste (and thus also the surface dose level) varies over a large range from 1 Bq/g for VLLW to about 10^8 Bq/g for some ILW. The shielding requirements during handling will thus be very different as well as the requirements for isolation during disposal.

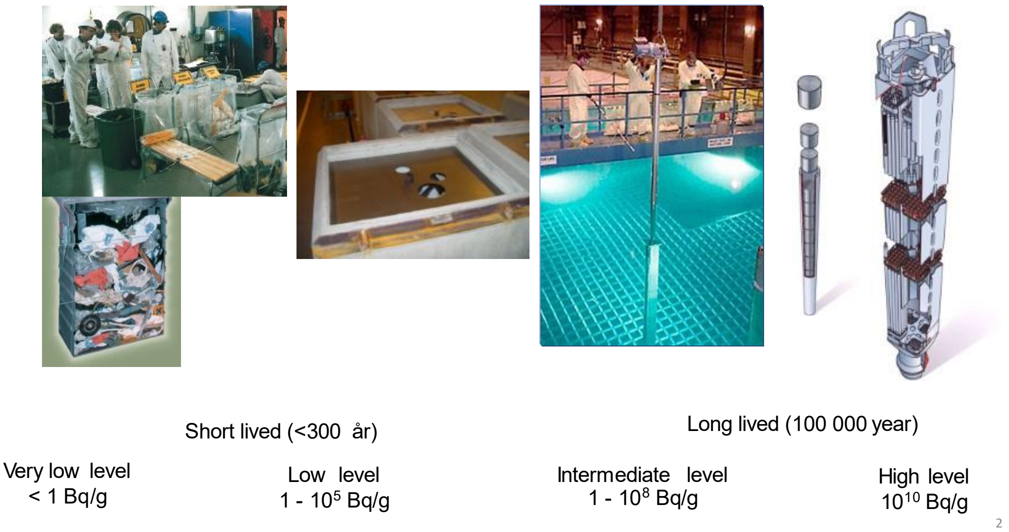

Figure 2-6. Examples VLLW, LLW, ILW and HLW/SNF from nuclear power production.

Most of the radioactivity, > 99 %, will be found in the SNF and in the structural components in the reactor core. The remaining < 1 % will be found in the process and technological waste, which is normally LLW.

The waste from nuclear power production can thus be classified as follows:

- **Spent fuel elements**, consisting of the fuel material (uranium oxide, plutonium oxide, fission products and transuranic elements), the fuel cladding and the structural components in the fuel element[3].
- **Core components and reactor internals**, i.e. components that hold the core together and that direct the flow of water (or gas) through the core. Examples are the core grid and core barrel. Also control rods are included among the core components;
- **Process waste**, i.e. waste from systems used during reactor operation to clean the process water or gas or to limit the releases of radioactive substances during operation;
- **Maintenance waste**, consisting of secondary waste generated during maintenance work and components (technological waste) from the reactor systems that have been replaced due to failure or wear or to renewal of the particular system;
- **Decommissioning waste**, with similar content as the maintenance waste. It also includes the reactor pressure vessel and its internal components, which are similar to the core components.

For a 1000 MW_e light water reactor annually about 20-25 tonnes of SNF, counted as uranium or uranium and plutonium weight (heavy metal (HM)), or 10-15 m^3 and about 100 – 200 m^3 (after conditioning) of LLW is generated. Some of this could also be VLLW. The volume of LLW will depend on the treatment and conditioning methods for the primary waste, in particular what methods are used for conditioning the waste from the water clean-up systems and what compacting methods are used for maintenance waste. The volume of ILW, mainly core

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[3] The management of the spent fuel is not discussed further in this report.

components varies depending on actions undertaken with the reactor and is normally at least an order of magnitude less than the LLW.

During decommissioning a few thousand m^3 of RW is generated. Most of this waste is VLLW or LLW, while some of the internal components are ILW.

During normal operation of a nuclear power plant some minor amounts of radioactive substances are released through the cooling water or with the off-gases. These amounts are strictly controlled and in compliance with regulatory limits. Such limits are set very low to ensure a very small radiological impact on the people and environment in the vicinity of the power plant. Different processes, e.g. filtration, ion exchange and evaporation, are used to minimise the releases. The normal operational releases from a power plant are not further dealt with in this report.

2.5 Free release of lightly contaminated material

An important factor for the volume of RW that will need disposal in a controlled way is the possibility to release some lightly contaminated or only potentially contaminated material for free use, either for disposal at a normal city dump or for recycling in the metal scrap industry. Free release falls under the category Exempt Waste and can be done in most countries. The free release is regulated by strict rules set up by the regulatory authority. In Sweden a procedure for the free release of such material has been agreed between the authorities, SSM, and the nuclear power operators [SKB, 2011]. It includes the following steps:

- Radiological mapping and categorization
- Decontamination
- Activity measurement
- Approval

In the first step the potential for radioactive contamination in the area where the waste comes from is mapped and typical radionuclide compositions (nuclide vectors) are established. In the second step a judgement is made if the radioactivity can be reduced by decontamination. In the third step the radioactivity of the waste is measured. As many of the radionuclides cannot be measured directly, their content is estimated using the nuclide vectors. Finally in the approval step it should be shown that the concentration of all relevant radionuclides is below the exempt value for this radionuclide, typically below 10 kBq/kg for the more important radionuclides in the waste. For transuranic elements this limit is 1kBq/kg.

All free release activities are documented and reported to the regulator.

3 Management routes for low and intermediate level waste and optimization

All types of RW, which is not exempt waste will require disposal. The management and conditioning of the different types of RW must thus be planned and performed in a way that considers all steps in the chain from original waste generation to disposal, i.e.

- Raw waste generation
- Sorting into different waste streams
- Treatment of the different waste streams, e.g. ion exchange, incineration, compaction
- Conditioning of the treated waste, e.g. solidification of ion exchange resins or ashes
- Packaging in containers suitable for the further handling
- Storage before transport to disposal
- Transport to the disposal facility
- Disposal.

Each of these steps will have specific requirements. In most steps the allowed radiation level of the product handled is limited and in several steps the product has to be solid to avoid risk of spreading of lose radioactive material during handling. Also characteristics like mechanical stability, chemical reactivity, weight, and size will be of importance.

Each step will have its specific waste acceptance criteria (WACs). In the end it is a question of optimizing the whole system, such that adequate safety is achieved in each step, while minimising the volumes to be disposed and the costs for the whole system. For instance, a balance has to be made between the cost of volume reduction by compaction and the cost of the corresponding disposal volume and the transport and handling of the waste packages. In the optimisation also the doses to the staff in the different steps should be taken into account.

Often, the most restrictive WACs come from the transports and from the disposal facility. Therefore, in most countries the WACs set by the disposal organisation and determined by the design of the disposal facility. The WACs are approved by the authorities. Often, the WACs do not take into account the special conditions of a specific waste generator, but are general for all.

However, when a waste management system is designed from the start taking all steps into account there is a possibility to optimize the system. As an example, in Finland all disposal facilities for LLW are located at the nuclear power plants. The waste packages can thus be transported in rather simple overpacks that provide shielding, but which do not have to follow the international standards used for transports on public roads. For disposal remote handling can be used. By allowing higher radiation levels on the waste packages, the radioactivity can be more concentrated in the waste package and thus require less disposal volume. In Sweden, where the disposal facility is in one site for four nuclear power plants, a similar saving is achieved by using large shielding containers. These are very heavy, about 100 tonnes, and can in a practical way only be handled by sea transports, which is the transport system developed in Sweden.

These examples shows that it is important to consider all aspects of the chain, when designing the radioactive waste management system. The issues of storage, transports and disposal should preferably be considered already when the treatment and conditioning system is chosen.

4 Low and intermediate level waste from the reactors considered in Estonia

This chapter describes the different waste streams that are generated during the operation of the different types of reactors, mainly process wastes. The physical, chemical and radiological characteristics of the waste are described as related to treatment, conditioning, packaging and disposal. Wastes arising from maintenance activities and decommissioning are also described.

As no details are available about the waste generation and types of treatment and conditioning methods for the SMRs considered for use in Estonia, the information provided in this and the following chapter is taken from the experience in present day reactors. It can be assumed that the SMRs will produce similar waste types, as the reactors are based on the same technology as present day reactors.

The most important operational waste streams from all types of proposed reactors are:

- Process wastes from water or gas clean-up systems
- Solid wastes from exchanged components
- Secondary wastes from maintenance activities

The solid and secondary waste streams generated by operation of a LWR or a GCR are similar, while the process waste streams differ as there is no water clean-up system used in the primary circuit of a GCR.

During maintenance several different types of secondary waste arise ranging from paper towels, rags, plastic and clothing to discarded equipment. Often this waste is compacted in a heavy duty press and packaged in the standard packages.

Process and secondary waste streams are generally LLW or VLLW.

No ILW is expected to be generated as process waste. However, some ILW, mainly control rods and other components positioned close to the reactor core, can be expected to be exchanged during the operational life of the reactor. The radiation level of these components is high but the volumes are small and they are normally stored together with the fuel for later treatment and conditioning in connection with the decommissioning of the reactors.

During decommissioning most of the waste is solid waste from removed components and concrete structures. There will also be secondary waste from the decommissioning activities, Also the usual operational waste including filters and ion exchange resins needs to be handled after the reactor ceases operation. Most of the decommissioning waste is LLW and VLLW. The most active waste from the decommissioning consists of irradiated components from within the reactor pressure vessel, which will need special handling. This waste is ILW.

4.1 Waste from the operation of light water reactors

As described in section 2.4 most of the radioactivity generated in a nuclear reactor stays in the fuel and the metallic material surrounding the fuel. Only small amounts are free to spread to other parts of the reactor systems. The main carrier of radioactive material in the reactor is the primary reactor coolant, which circulates through the core and the pressure vessel and carries the heated water to other systems to generate steam and drive a turbine to generate electricity. All surfaces that are in contact with the primary coolant will potentially be contaminated and need to be taken care of as RW. Components adjacent to the reactor core will also be subject to activation.

In Figure 4.1 a simplified diagram is shown of the reactor systems for a PWR.

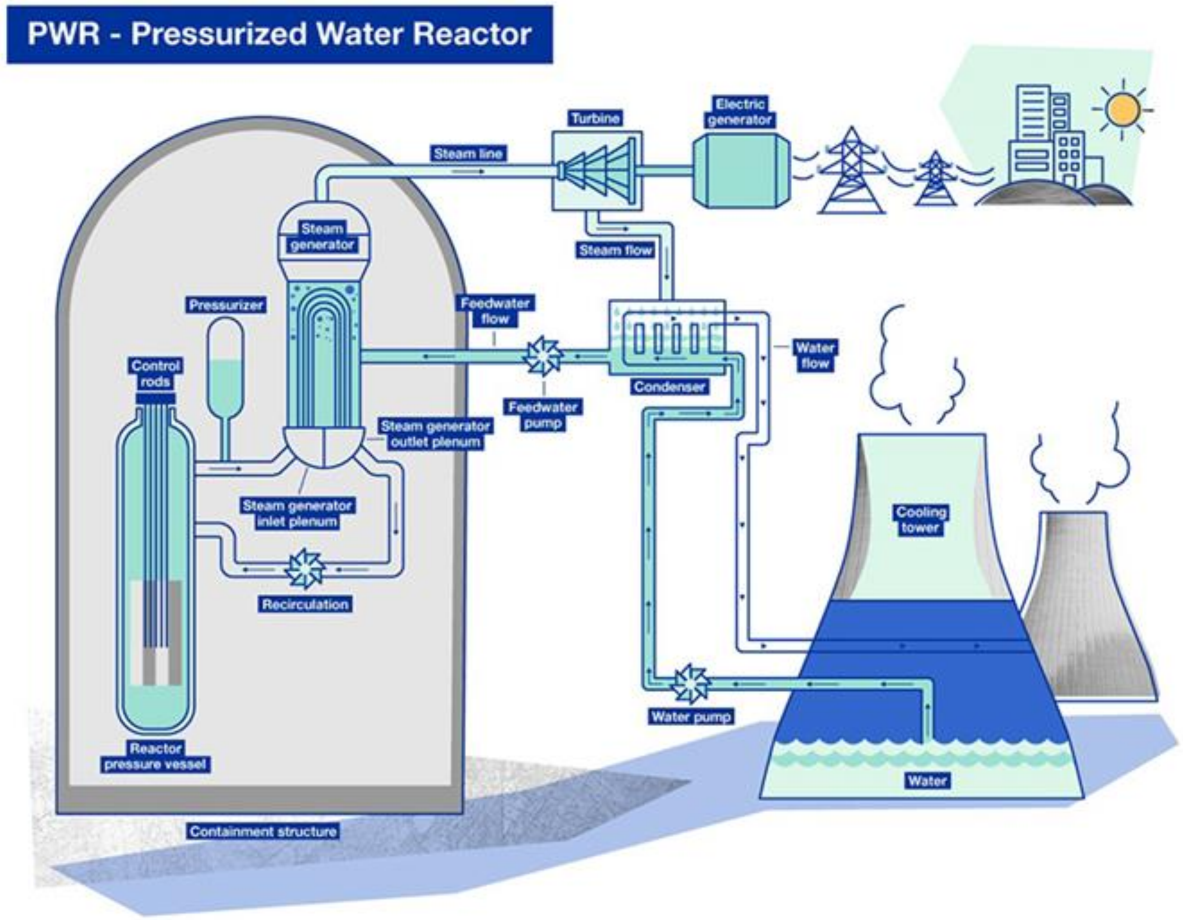

Figure 4-1. Schematic of a typical PWR [IAEA,2021].

The primary coolant system circulates through the core and the steam generator(s) as well as the pressurizer. There is a reactor coolant cleaning system (not shown in the figure) that circulates part of the coolant through filters and ion exchangers before returning it to the reactor. The secondary system exchanges heat with the primary coolant system via the steam generator tubes. The secondary system includes the turbine and condenser. Water in the secondary system does not mix with the reactor coolant or come in direct contact with contaminated surfaces. Thus this water is handled as non-radioactive.

A BWR circulates the same water through the reactor and the turbine, so both systems are radioactive, though the turbine less so.

The most important types of waste generated during the operation of a light water reactor are shown in Table 4-1. The table also describes the physical and chemical form of the waste as well as the typical level of radioactivity in the waste.

Table 4-1. Characteristics of the most important RW streams generated in a light water reactor.

Waste stream	**Physical**	**Chemical**	**Radiological**
Ion exchange resins	Slurry	Organic, ions	High radionuclide content
Evaporator concentrate	Slurry, abrasive particulates	Corrosive, salts,	Potentially high radionuclide content
Filters	Solid	Metal, charcoal	High radionuclide content
Secondary waste	Solid	Organic, plastics	Low radionuclide content
Exchanged components	Solid	Metallic	Radionuclide content varies
Oils, solvents	Liquid	Organic, flammable, corrosive	Low radionuclide content

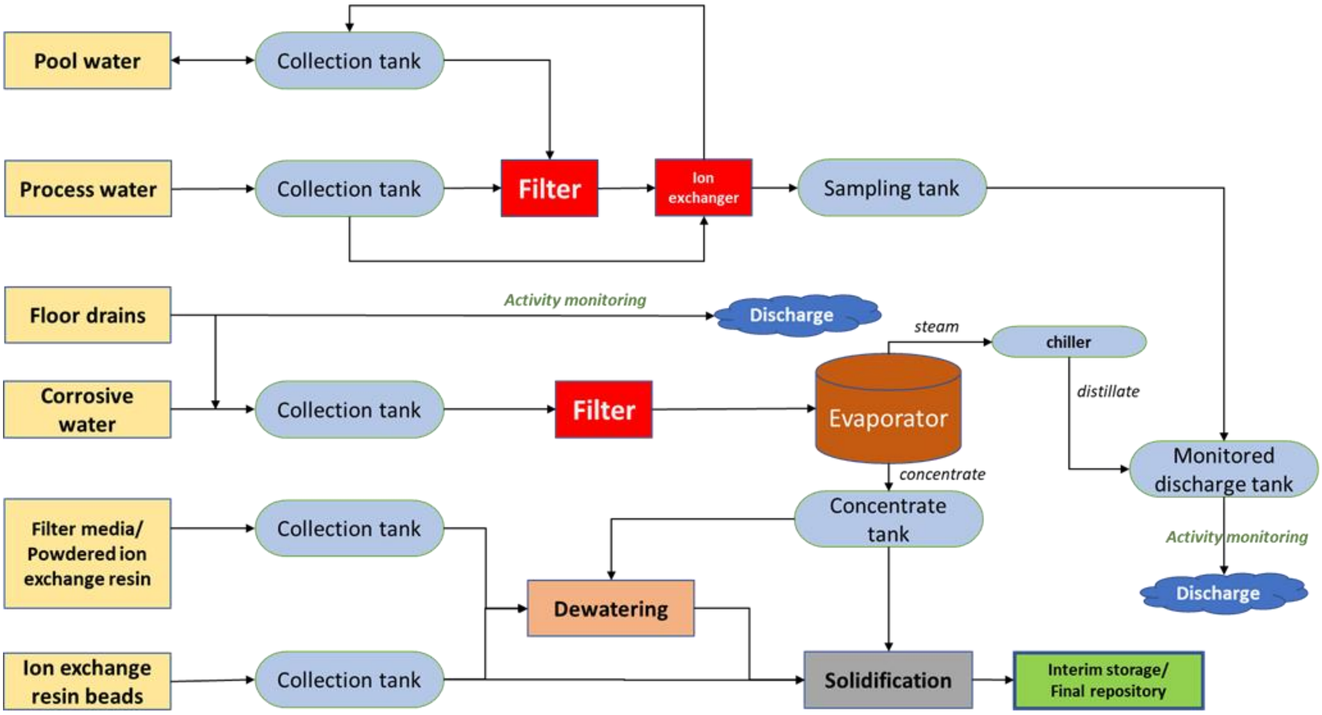

Figure 4-2. Flowchart of typical waste streams.

A primary source of process waste comes from the clean-up of water used and collected at different places in the reactor systems and buildings. An overview of these different waste streams is given in Figure 4-2.

The most active LLW emanates from the clean-up systems in the reactor itself, where the circulating reactor cooling water is passed through mechanical filters and ion exchange resins to ensure that the water passing through the reactor is very clean.

Another RW form resulting from water clean-up is evaporator condensate, which remains after evaporating excess waste water to reduce the volume. An alternative process, reverse osmosis, also produces a condensate fraction which can be treated similarly.

Specific characteristics of PWR waste that differentiate it from BWR waste result from the difference in reactor design where the secondary system that powers the turbine in a PWR plant is not radioactive. Furthermore, the reactor coolant water may contain boron[4], which ends up in the process waste streams. Boron inhibits the curing of concrete, so the concentration in the conditioning process needs to be monitored.

The design of the BWR, where steam from the reactor coolant drives the turbine means that the secondary side of the plant is also radioactive. One important waste component comes from the filtering of the reactor water condensed in the turbine before reinjecting it in the reactor. The activity level on the turbine side is, however, much lower than the in primary system. This results in larger quantities of VLLW arising from maintenance activities on the turbine side of the plant.

4.2 Waste from decommissioning of LWR

The potentially radioactive waste that arises when a LWR is decommissioned is very similar to process and maintenance waste that is produced during operation of the reactor with the addition of concrete structures that need to be dismantled. This dismantling is necessary in order to access other components and sometimes the concrete is irradiated or contaminated from leaks or spills and needs to be managed as radioactive waste. Some of the components removed during decommissioning could be quite large and will require special handling, while most of the components are smaller and can be handled in the same way as during normal maintenance work.

The volumes of waste to be managed from decommissioning will be significantly greater than those that are generated during operation. The fractions of waste in different categories will also differ from operational waste in that the reactor pressure vessel itself and its internal structures are being dismantled, resulting in ILW. The usual operational waste including filters and ion exchange resins also needs to be handled after the reactor ceases operation.

The most active components to be handled are those from inside (reactor internals) and adjacent the reactor pressure vessel. These components include steam dryers, steam separators and the core shroud from a BWR and the thermal shields and core supports in a PWR.

The design of the PWR reactor core is such that the adjacent components are subject to higher neutron flux and become more activated that they generally do in a BWR, especially the reactor pressure vessel, which often produces more long-lived ILW compared to a BWR.

Also the pressurizer and steam generators from a PWR are usually heavily contaminated with high dose rates at the time of decommissioning.

Thus while there may not be a need for new waste handling processes and methods in order to carry out decommissioning, they will be applied on a larger scale.

4.3 Waste from operation and decommissioning of gas-cooled reactors

Operational waste

The information available concerning waste generation in a gas cooled reactor is more limited than for LWRs.

The proposed MMR design uses no water in the reactor. However some water treatment capacity may be needed to handle water used for washing and decontamination.

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[4] The UK SMR does not use soluble boron in the reactor core. NuScale uses boron.

Otherwise, secondary waste streams will be similar as for light water reactors.

Decommissioning

For a GCR the management of waste generated during dismantling is more complicated than for a LWR. In particular the graphite moderating material surrounding the fuel will cause concern. Today, there is no accepted disposal route for irradiated graphite available in the world. Studies are underway for Russian, French and UK reactors with graphite cores.

The radioactive graphite coming from nuclear installations has different characteristics than other RW due to its physical and chemical properties and also because of the presence of tritium, carbon-14 and Clorine-36. Even after many years of irradiation, graphite retains most of the good mechanical properties and is relatively insoluble and not otherwise particularly chemically reactive. While graphite appears therefore to fulfil most of the general requirements for a solid RW form suitable for disposal the evaluation of the radioactivity inventory of graphite moderators and other details of graphite used in nuclear reactors show that this graphite cannot be accepted by existing disposal sites without particular conditioning.

The graphite in some of the low temperature reactors contains a considerable amount of stored Wigner energy. Unexpected release of Wigner energy, mainly in the older graphite moderated reactors, has caused several incidents. Potential risk connected with accumulated Wigner energy is one of the main factors which has to be taken into account during graphite waste processing and disposal.

Problems in the RW management of graphite arise mainly because of the large volumes requiring disposal, the long half-lives of the main radionuclides involved and the specific properties of graphite - such as stored Wigner energy, graphite dust explosibility and the potential for radioactive gases to be released.

Various options for the management of radioactive graphite have been studied but a generally accepted approach for its conditioning and disposal does not yet exist. Different solutions may be appropriate in different cases. A final and generally accepted solution for the conditioning and disposal of radioactive graphite has not yet been decided.

5 Treatment, conditioning and packaging

5.1 Requirements that govern the treatment, conditioning and packaging of radioactive waste streams

In the process of preparing the RW for disposal the waste is successively treated to reduce the volume and adapt the chemical characteristics, conditioned to get a solid product and packaged to be possible to handle. The application of treatment and conditioning methods and the selection of packaging are dictated by the waste acceptance criteria for interim storage and final disposal. Repeated handling (reconditioning or repackaging) of the waste should be minimized.

In general, the waste acceptance criteria specify the maximum radionuclide-specific activity and the maximum surface dose rate for the waste package, and also the mechanical strength. The waste shall be verified to not contain free liquids or chemicals that can lead to reactions or degradation of the package or the final repository.

The waste packaging shall be specified so that the handling, storage and disposal can be carried out safely and efficiently. This is generally achieved by specifying the dimensions, weight and material of the filled waste packages.

The purpose of solidification is to bind the radionuclides or the radioactive particles in a solid matrix, which together with the packaging limit the risk of release of radioactive particles from the waste by providing multiple barriers. Some packages also provide shielding such that they can be handled without extra shielding, while others will need a shielding overpack during handling or even remote handling. The packages are maintained clean on the outside so that they can be safely handled.

Waste management should be simplified so as to minimize the number of different packages used even if the models selected are not optimal for every waste type. Such an approach allows waste package storage and handling equipment to be simplified, enhancing safety and handling while reducing costs.

5.2 Treatment and conditioning of wastes from operation – overview

A typical waste stream map for a LWR is shown in Figure 5-1. Each waste stream, whether solid or liquid, needs to be sorted or separated to facilitate efficient handling. Each waste stream has a final disposition, whether it be free-release or discharge or final disposal.

5.3 Spent ion exchange resins

Ion exchange resins are small plastic beads (they look like caviar) or powder. When they are no longer effective (spent) they are replaced and solidified in suitable packages. The resins typically contain radioactive corrosion, fission and activation products, depending on reactor operations and the systems being filtered. Events in the plant, such as fuel failures, will affect the activity captured by the ion exchange resins.

Spent ion exchange resins are collected and stored wet in tanks before being pumped to the waste conditioning system, which can be a permanent system in the plant or a mobile system. Wet resins are typically dewatered and mixed with concrete in drums or other standard containers in order to render the waste homogenous in solid form. The most frequent solidification method is by cementation. In some countries, both in Sweden and Finland, other methods involving drying and solidification in bitumen are used. The resins must be heated and the water driven off before mixing with bitumen. Bitumen is an organic material and can pose risks during long-term storage, including with respect to degradation and fire safety.

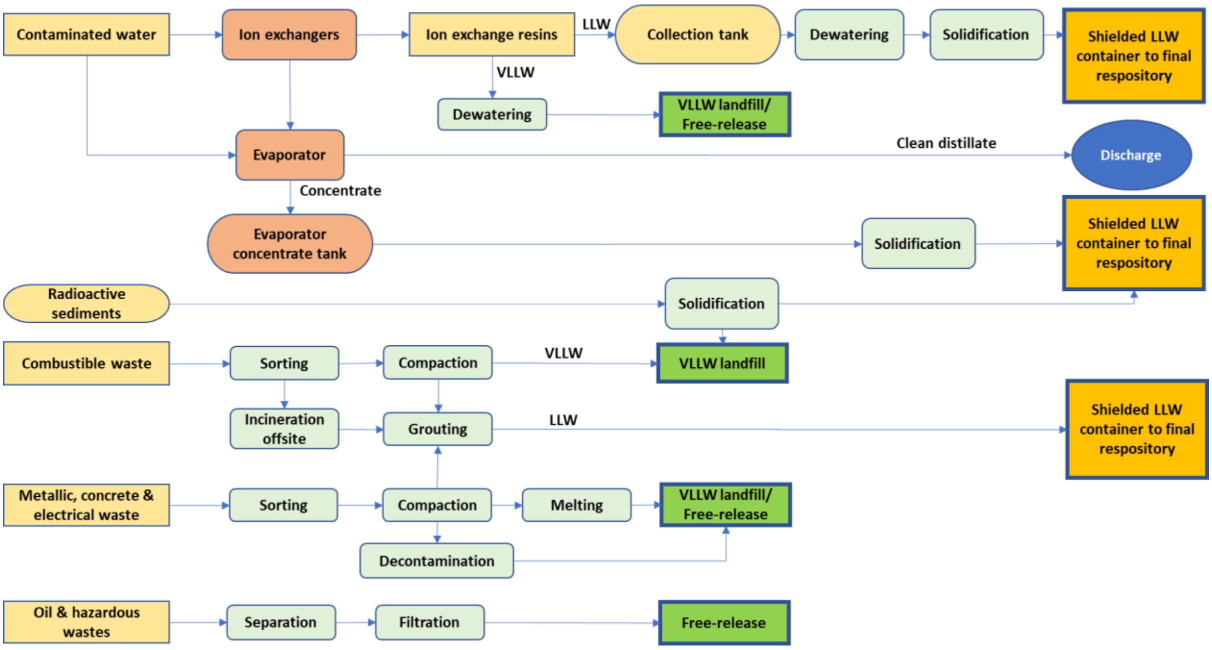


Figure 5-1. Example flow diagram for typical waste streams from a LWR.

There are also waste solidification systems in Korea and UAE that use polymers combined with hardener as a matrix material. The polymer solidification method has many advantages including superior compressive strength, durability, chemical resistance and low leachability. Polymerization agents used in Korea include epoxy resin mixed with polyamides and aliphatic amines.

More advanced treatment methods exist but are not widely used in the nuclear power industry. These include pyrolysis and plasma incineration.

The use of cement as a solidification matrix is less efficient with respect to final waste volume than other materials. The water content of the spent resins is an important parameter in successfully applying this treatment method; excessive water content can result in accumulation of free water in the package during storage while insufficient water will negatively affect the integrity of the waste matrix.

Blending with bitumen allows more resin to be included in the same volume, but the resin must be completely dry to avoid the formation of steam bubbles in the matrix.

Selection of a matrix material should be based on the following considerations:

- Waste loading – quantity of waste that can be blended with the matrix (typically 25-45% by weight)
- Ease of production
- Durability of the waste form
- Radiation stability
- Chemical flexibility
- Compatibility with the disposal environment
- Ability to prove safety for the long-term disposal

Some resins with lower activity concentration can be dried and packaged without solidification.

5.4 Liquid waste

Liquid waste is collected and stored in tanks before being sent for treatment and eventual discharge or disposal as conventional waste.

5.4.1 Water treatment

Filtration

Various types of filtration systems are used to remove as much of the activity as possible. These filtration systems usually consist of ion exchangers, reverse osmosis and mechanical filters.

In addition to conventional organic ion exchange resins there are systems that use natural or synthetic zeolites. The main advantages of synthetic zeolites when compared with naturally occurring zeolites are that they can be engineered with a wide variety of chemical properties and pore sizes, and that they are stable at higher temperatures, though these properties come with a higher cost [IAEA, 2002].

Other synthetic ion exchange materials have been engineered to remove specific nuclides such as cesium and cobalt. Such materials developed at the Loviisa NPP in Finland are currently in use at several reactors and in the system to treat radioactive water that accumulated the buildings of the Fukushima Dai-ichi NPP after the accident of March 11th 2011 [Fortum, 2021].

Evaporation

Evaporation is a very effective method for removing radionuclides from water. Certain radionuclides such as ^{137}Cs are present in a soluble state and can be removed by evaporation if necessary to meet discharge limits.

Evaporation results in two waste streams: the cleaner distillate and the residue condensate. The distillate should be suitable for discharge while the evaporator concentrate, which contains most of the radioactivity, is solidified in a similar way as the ion exchange resins by drying and mixing with a solidification matrix material. Sediments collected from tanks and drains can be similarly handled. The processing of any water from laundry activities can pose special challenges due to the presence of surfactants.

The packages used for the solidified wastes resulting from water treatment are either cylindrical drums or cubic packages fabricated of steel or concrete.

5.4.2 Other liquids

The operation of any industrial plant involves the use of lubricating agents and solvents. These products should be carefully controlled to prevent the generation of mixed waste (hazardous and radioactive). Many such liquids can be distilled or filtered to remove radioactive particles, allowing them to be free-released for treatment and disposal at a conventional facility. Other methods involve incineration.

5.5 Solid waste

5.5.1 Secondary waste

Secondary waste arising from maintenance and decommissioning activities will vary in nature so it should be sorted in accordance with the intended treatment and destination. Such waste is generally highly compressible. This VLLW waste not requiring further treatment is usually compacted in a heavy duty press and packaged in the standard packages.

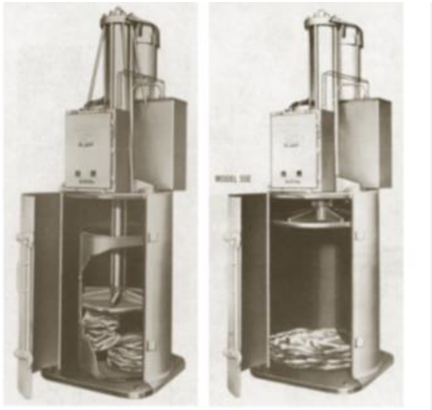


Figure 5-2. Simple compactor installation for in-drum compaction of VLLW.

Combustible waste can be further reduced in volume and rendered inert through incineration. The product of this treatment is radioactive ash. Generally this waste form can be immobilized in a matrix material to render it less dispersible before final disposal. The chemical composition of the ashes needs to be known in order to meet any waste acceptance requirements for the final repository.

5.5.2 Exchanged components

Exchanged components will as much as possible be repaired and reused to avoid generation of waste that needs disposal. They are also cleaned (decontaminated) and the cleaning water is treated by evaporation as described above. Components that even after decontamination are designated as RW will be packaged in similar packages as those described above. In some cases even larger packages can be used up to standard sea shipping containers for VLLW.

Some metallic waste can be further reduced in volume and even free-released through melting. The products of this treatment are metal ingots and slag. Often the radionuclides are concentrated in the slag, which can be disposed of separately. The reduced activity in the ingots means that they are suitable for free-release or decay storage. Decay storage involves the storage of waste containing short-lived nuclides until the radioactivity decays to a level that permits free-release.

5.5.3 Filters

The mechanical filters used for treating radioactive liquids are solid bodies and are normally packaged directly in suitable packages and grouted in concrete.

5.6 Waste from decommissioning of the reactors

When planning decommissioning of a reactor it is advisable to have access to a detailed history of the plant so that an assessment can be made of potentially contaminated areas and structures. Those areas and structures that can be assured to be free of radioactive contamination can be dismantled using conventional methods, which is quicker and less expensive.

Those areas and structures that are subject to contamination need to be verified before proceeding with dismantling. A risk-based approach is often applied in making these determinations.

The dismantling of known radioactive structures needs to take place with appropriate radiological controls. After decontamination it should be possible to free-release much of the waste.

In contrast to the meticulous methods required when a component is to be replaced during the reactor’s operating life it is appropriate to apply more destructive and rapid methods to cut piping and other components during decommissioning. Destructive decontamination methods can also be employed if it is judged advantageous to reduce the level of contamination in systems or components. An overview of the waste management during decommissioning is shown in Figure 5-3 [SKB, 2013].

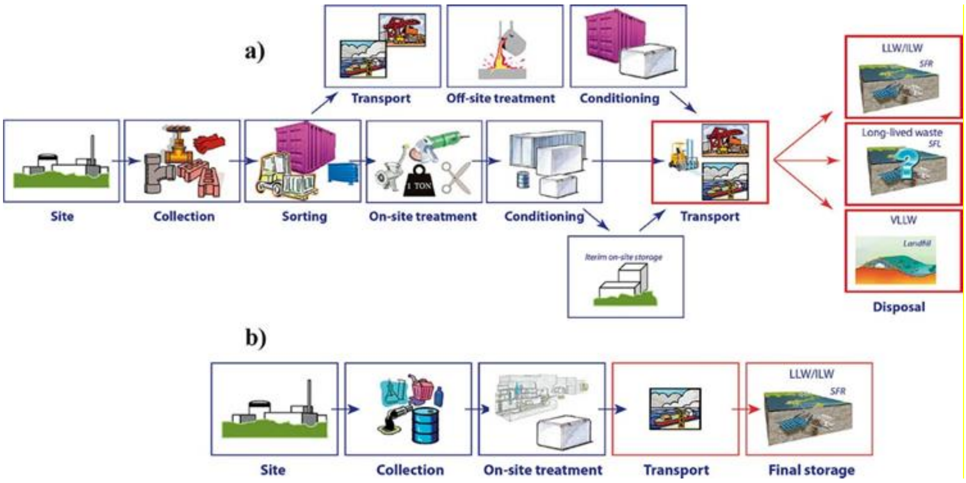


Figure 5-3. Waste routes for a) sold waste and b) contaminated liquids during decommissioning.

5.6.1 LLW and VLLW

Most decommissioning waste will be LLW or VLLW, with low levels of radiation and with contamination dispersed throughout the waste. This means that much of the dismantling operations can be carried out with minimal provisions for shielding, though controls are necessary to prevent the spread of contamination, especially while cutting or using other methods that generate particulates.

5.6.2 ILW

For ILW or even LLW with higher dose rates it is necessary to plan for remote handling of the components, possibly under water. The reactor systems that are connected or close to the reactor pressure vessel and thus the core will typically produce such types of waste. These include the reactor vessel, the steam generators and primary coolant pumps, for example.

Shielded packaging will be required to handle and store this waste. The Swedish reactors use a packaging and handling system that allows cassettes to be loaded with ILW components in the reactor pools before being lifted remotely within a shield into large rectangular steel tanks. These tanks are approximately 3 m x 1 m x 2 m (LxBxH) with a wall thickness of 50-150 mm and are designed to be transported and stacked for storage and disposal. The size of these tanks allows dismantling to take place with fewer cuts producing larger pieces. Other systems in use involve cutting the reactor components into relatively small pieces in order to fit into smaller packages.

5.7 Waste packages

For the safe handling of the RW it should be packaged in suitable waste packages. These should be essentially free of contamination on the outside and tight to avoid release of radioactivity from the packaged waste. In addition, the packaging can provide radiation shielding to simplify the handling. This is normally achieved by using thick concrete or steel walls in the package.

The most common waste package in the world is 200 l common oil drums. They were easily available and cheap. With time more specialised packages have been developed. Examples are the concrete walled packages and larger steel packages. Today even the simplest 200 l drums are made of stainless steel.

Figure 5-4 shows some of the waste packages used in Sweden for LLW. They range from standard 200 l drums to large standard shipping containers. In addition to the packages shown the robust steel tanks described in 5.6.2 are used for strongly irradiated core components.

VLLW, which can be disposed in disposal facilities on site is normally packaged in plastic bags.

Figure 5-4. Different types of packages for LLW used in Sweden.

5.8 Volumes of waste for disposal

As there is no historical information yet available concerning waste quantities generated from the operation and decommissioning of SMRs it is not possible to produce a verifiable estimate of the waste volumes that will require disposal. Some information can be collected from the experience from the present day reactors, but new developments could change the estimates substantially.

In this section first a discussion is presented of the parameters that will affect the volumes of waste and then a rough estimate is provided based on scaling the experiences from present day larger reactors. The results should, however, be used with caution. They should not be seen as a prediction of exact volumes but more as an indication of the order of magnitude of waste volumes that will require disposal. Before actually planning for storage and/or disposal facilities a more detailed assessment will be needed. By that time experience from the operation of SMRs in other countries can be taken into account, as well as detailed decommissioning studies.

5.8.1 Parameters affecting volumes of waste from operation and decommissioning

While it might theoretically be possible to calculate the quantities of radioactive waste generated during the lifetime of a nuclear power plant that is operated perfectly, there are in reality a number of parameters that will affect the characteristics and quantities of the waste. Some examples are:

- Physical size of the reactor and associated systems, as well as the reactor buildings.
- Clean-up systems design
- Events during operation
- Available waste disposal routes
- Permissible levels of release of radioactivity to the environment during operation
- Activity limits for free release of waste
- Decommissioning strategy

Estimates can be made based on scaling from larger reactors. Waste quantities are probably not correlated with power, rather with the physical size of the reactor and adjoining systems, though at a higher level (m^3/MWe) than for a large reactor of the same type.

The design of the reactor coolant water clean-up systems determines the types and quantities of radioactive filter media that require conditioning and disposal.

Decades of reactor operation show that the most drastic increases in waste quantities result from the effects of accidents where radionuclides that should be confined in the fuel are released. Even recurring minor fuel failures can raise the activity in the waste over the operating life of the plant. Errors in operation in the waste processing systems can render waste management more difficult. For example, if waste is directed to the wrong tank or waste streams are accidently mixed. Inleakage of seawater can also cause problems as the presence of concentrated chlorides can overwhelm the ion exchangers.

Uncertainty in waste disposal routes due to, for example, the lack of an approved final repository will affect waste management and thus the quantities requiring disposal. If the waste acceptance criteria are not established then it may not be appropriate to process the waste for final conditioning, in case further treatment might be necessary. If there are no provisions for free-release of waste or for disposal of VLLW as a separate category then the quantities of LLW will be increased.

Regulations governing radioactive releases and radiation safety tend to become more stringent over time which in turn leads to more restrictive WAC requirements. The effect of these changes can make waste management more complex and costly, though they do not necessarily result in the production of more waste. The Swedish nuclear fleet has succeeded in significantly reducing waste generation by, for example, restricting the materials that are permitted into controlled areas and systems.

The ultimate strategy for decommissioning the plant will affect the quantities of waste requiring disposal. A green-field end state requires that radioactivity be removed from the site to a very low level. A different end state may be defined that permits some structures and building materials to remain in place even if some activity is present, depending on the planned use of the site.

5.8.2 Rough estimate of waste volumes that will need disposal

The volumes of LLW generated from a 1200 MW_e reactor is typically between 100 and 150 m^3/year. As much of this is maintenance waste it can be assumed that the waste generation is not fully proportional to the electrical capacity. For a 300 MW_e reactor the waste generation can thus be estimated to about 50 m^3/year packaged waste. Thus, from operation of 4 reactors of this size under 60 years about 12 000 m^3 will be generated, half of it probably being VLLW. This estimate is judged to be the correct order of magnitude with the condition that more detailed estimates need to be made when more data is available.

Preliminary estimates for the decommissioning of PWR Ringhals 2 in Sweden indicate that about 4 000 m^3 packaged waste will be generated [SKB, 2013]. Of this about 15 % will be VLLW, 70 % LLW and 15 % ILW. Assuming that the waste volumes from decommissioning a 300 MWe reactor is about 40 % of that from a large reactor, about 1 600 m^3 will be generated per reactor or in total 6 400 m^3 for 4 small reactors. Of this 1 000 m^3 will be VLLW, 4 500 m^3 LLW and 1 000 m^3 ILW. The distribution of the waste categories will be heavily dependent on how much effort is devoted to sorting and decontamination. The total amount of activity (Bq) will remain the same. The calculation also assumes that there are national regulations for allowing free release of exempt waste.

Thus in summary the amount of RW that need to be taken care of from this nuclear programme is about 7 000 m^3 VLLW, 11 000 m^3 LLW, and 1 000 m^3 ILW.

6 Interim storage

Interim storage is an essential function in the logistics of operating a nuclear power plant. This entails available facilities with capacity for interim or buffer storage of RW after it is packaged and awaiting transport to a central interim storage or final disposal facility

Facilities for interim storage of RW are designed to provide the appropriate environment for a specified time. The integrity of the waste packages needs to be maintained so that they can safely be transported to a treatment or final disposal facility.

Such facilities need to shield the waste packages in order to protect the workers and the public from radiation exposure. Properly packaged waste should not pose a risk of radioactive contamination so filtered ventilation is not generally necessary, though monitoring of exhaust air may be required.

There are two general categories of interim storage that are used in the nuclear power industry today: area storage and engineered storage. Both are used at Swedish nuclear facilities.

Area storage, also known as open vault storage, consists in emplacement of waste packages on the ground or on a constructed base, either in the open air or with a simple open sided covering.

Figure 6-1. Container yard

Engineered storage refers to any fully contained building or structure specifically provided for the storage of waste packages. Engineered store designs are in many cases based on the need to handle large volumes of drummed or boxed waste packages with substantial surface dose rates. These stores may range from simply constructed enclosures to highly engineered facilities incorporating shielding structures and remote handling equipment, fully serviced with ventilation, effluent collection and instrumented controls.

Such facilities used in Sweden include buildings and underground caverns adapted for interim storage.

6.1 Safety and design

RW may be present in several forms as it passes through the treatment and conditioning processes. It may exist sequentially as raw, liquid, treated, immobilized and fully conditioned waste. While in interim storage the waste should be expected to retain its form and suitability for transport and disposal for up to 50 years without subsequent reconditioning. This is accomplished through the interaction of three sets of criteria:

- the waste acceptance criteria (WAC),

- the waste form and container specifications, and
- the design and operating requirements of the storage facility.

The safety principles that apply to the design and operation of interim storage facilities include those that apply to all aspects of handling radioactive material.

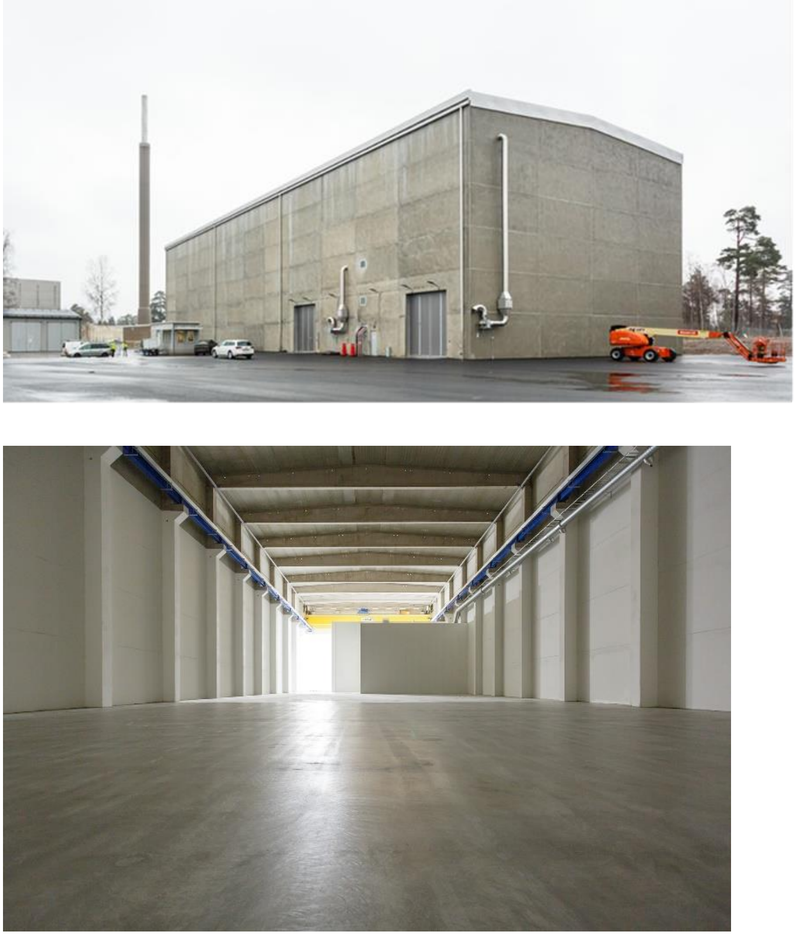


Figure 6-2. New storage building for RW at Studsvik. (Courtesy of Svafo)

Figure 6-3. Interim storage of overpacked drums.

The employees and public must be protected from undue radiation exposure, not to exceed specified dose limits. Further, the environment must not be harmed by the storage operation. Implementation of these principles usually entails multiple barriers and monitoring to the extent required by the nature of the waste. A more robust packaging for the waste can allow a simpler construction for the interim storage facility.

Other considerations that should be taken into account are the need to store separately wastes containing hazardous chemicals from non-hazardous wastes. The storage of radioactive hazardous waste will impose additional constraints on interim storage, including both the facility design and the administrative controls governing waste management.

The storage facility must function as an integrated part of the entire waste management system.

An engineered storage facility is usually provided with an area for inspection, certification and labelling of waste packages. The storage facility is usually divided into areas where low contact dose rate packages are stored, areas where packages not meeting WAC are stored and a shielded area where high contact dose rate packages are kept secure.

Provision for maintaining a database keeping chain-of-custody for each waste package in storage must be included in the design. Key information about the waste package should include the total radionuclide content, the waste matrix used for immobilization, the treatment and/or conditioning method and the unique package designator.

Engineered storage facilities should be designed to allow control of any contamination from gaseous or liquid releases. Adequate ventilation should be available to deal with any gas generation during normal operation or possible accident conditions.

Storage facilities are often built in anticipation of a need, and have inherent limitations in the types and quantities of waste packages they might receive. Typically the initial design often needs to be changed in terms of space required, floor loadings and type of waste storage required. The storage capacity of the facility must be designed to accept the maximum operational waste anticipated from the plant. Storage of subsequent decommissioning waste arising should also be considered.

The design of an interim storage facility should take into account that it might be one of the last buildings in use at a site so it is desirable to minimize maintenance requirements.

Figure 6-4. Berkeley interim storage facility, UK [IAEA, 1998]

7 Transport of radioactive waste

At some steps in the management chain for RW, the waste will have to be transported outside of the nuclear power plant or sometimes only within the perimeter of the power plant. This includes transports to storage facilities as well as later to a disposal facility. Sometimes also transports to treatment and conditioning facilities are used, e.g. to an incinerator or melting facility.

If the disposal facility is located at the site for the nuclear power plant internal transports can be used, which have to fulfil high safety standards, but which are not subject to national and international transport regulations.

If a transport is undertaken on public roads or by sea they have to fulfil the international transport regulations.

7.1 International transport regulations

The transport of SNF and RW is regulated by national authorities and based on the IAEA transport recommendations [IAEA, 2009b]. These guidelines have then formed the basis for the international regulations regarding transportation on sea, road and railroad.

The purpose of the transport regulations is to avoid harmful consequences from the radioactive material in case of accidents. To this end the containers will have to be designed to withstand without leakage a number of defined impacts, such as falling from a height, penetration, immersion in deep water and fire.

The main items in requirements and regulations for transport of RW are:

- Minimum requirements on type of transport container to use. These requirements depend on the properties (general, radiological, chemical and mechanical) of the material, e.g. solid/liquid waste form, radionuclide content, etc.
- Regulations with regard to highest permissible radiation levels on the surface of the waste containers and at a certain distance (1 or 2 m) from the container.
- Labelling and classification with regard to radiation levels.
- Regulations for handling and loading (including loading together with other goods).
- Checklists in the event of emergencies (for transport and emergency staff).
- Requirements on the transportation documentation.
- Security/Physical protection.

The strongest requirements are for the packages used for the transport of SNF. These are so called type B packages and should withstand falling from 9 m height, immersion to 200 m depth and a fire of 800 degrees for half an hour.

For packages used for LLW the requirements are less severe as the consequences of a possible release are much less. LLW packages that by themselves fulfil the requirements can be transported in simple standard shipping containers, while packages with a higher dose rate will need to be transported in sturdy thick walled containers. In many cases it should be enough to fulfil the requirements for so called LSA or type A containers, while in some cases with a higher activity concentration type B containers will be needed.

LLW can be transported on trucks, trains or ships, depending on the location of the nuclear power plant and the repository. Each transport mode has its limitations and restrictions, e.g. on size or weight.

Although the prime aim of the transport regulations is to ensure that radioactivity is not released during an accident, emergency arrangements are a key element in the planning of off site transports. The waste transporter is responsible for assuring emergency response for incidents. Emergency drills and exercises are important to ensure the availability of the response capacity.

7.2 Land transports

Land transports are used in most countries. Depending on the availability of railways close to the nuclear power plant and the disposal facility the transports can be made by rail, which can take heavier loads, or by lorries. In France e.g. train transports are exceedingly used for the transports from the nuclear power plants to the central disposal facility at Centre de l'Aube. Some lorry transports are also used. In South Africa or in the United States to a large extent lorry transports are used.

Figure 7-1. Transporting LLW to Vaalputs disposal facility in South Africa.

Figure 7-2. Transporting ILW to WIPP disposal facility in USA

Figure 7-3. Transporting LLW by train in France.

Also in Sweden, where most of the transports are by sea (see below) some transports of VLLW and LLW are made by lorries in standard shipping containers. This is e.g. the case when waste is transported to Studsvik for incineration or melting. Although standard shipping containers are used, they are clearly marked that they contain radioactive goods in accordance with the transport regulations.

7.3 On site transports

Transports of RW are needed on the site of the NPP, e.g. from the conditioning facility to an interim storage and to the disposal facility if this is built at the same site. This is for instance the case at the Finnish NPPs at Olkiluoto and Lovisa. Although the formal requirements are lower than for transports on public roads the safety of the staff and the local environment will still be determining the requirements on the transports.

The transports are made with shielded trucks to avoid radiation dose to the staff and in solid overpacks. An example is shown in Figure 7-4.

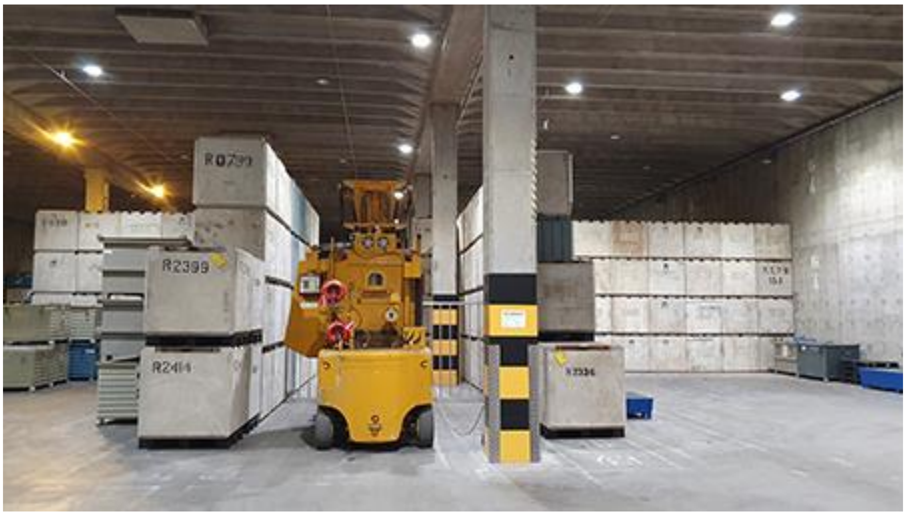


Figure 7-4. Shielded fork lift truck for transport of RW packages in Ringhals, Sweden.

7.4 Swedish sea transport system

All nuclear facilities in Sweden are located at the coast. It has thus been very practical to develop a transport system based on a ship using large and heavy transport containers. The ship has been specially equipped for nuclear transports, in particular with special arrangements for physical protection and was designed to withstand collisions. It has been designed both for the transports of SNF and LLW. As the ship is a so called roll on roll off ship it can take very heavy loads which can be driven on board like on a ferry boat. The ship is shown in Figure 7-5.

Figure 7-5. Loading of a transport container for LLW onto the Swedish ship dedicated for SNF and RW transports.

For the transport of LLW large shielded containers are used, weighing up to 120 tonnes. Different thicknesses of the shielding walls are used. The thick shielding in the container means that waste packages with high dose rates can be accepted, up to 500 mSv/h on the surface, while still following the transport regulations demand of 0,1 mSv/h at 1 metres distance from the transport container. Also the loading and unloading of the transport containers are done remotely. See Figure 7-6.

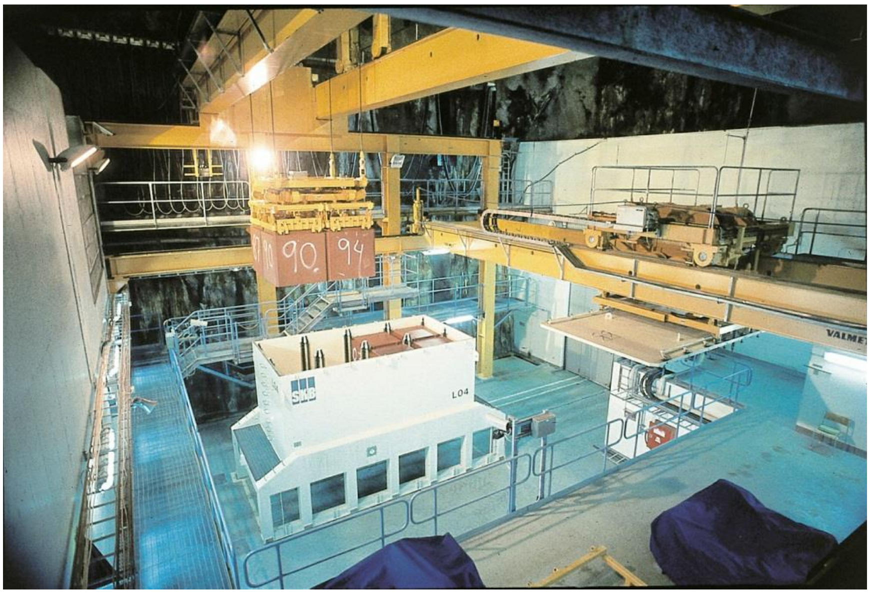


Figure 7-6. Remote unloading of a shielded transport container in the SFR repository in Sweden.

The Swedish transport system has been used for more than 35 years with no incidents and is operating routinely between the four nuclear power plants, the interim storage for SNF and the disposal facility, SFR, for LLW. Also transports from the Studsvik research facility to SFR are made by the ship.

By early development of the transport and disposal system it has been possible to optimize the RW management system and make it possible to lower the final disposal volume by putting more activity into the waste packages.

8 Disposal of radioactive waste

8.1 Alternatives for disposal

In reality there exist four main concepts for disposal of RW.

- Disposal on the surface in simple trenches.
- Disposal in engineered structures on or slightly below the surface
- Disposal in engineered structures in rock caverns at 50 – 200 m depth
- Deep disposal in mined tunnels or caverns at 400 – 1000 m depth.

Their application will depend on the radioactivity level and the longevity in the RW. Also other factors like geological conditions in the country, size of the nuclear system and public acceptance can influence the choice.

A fifth concept has been proposed but still not implemented. This is disposal in very deep boreholes. This is only considered for small volumes of HLW or SNF. The safety of such a facility has not yet been proven and is not further considered in this report.

Simple trenches are used for VLLW, but in several countries VLLW can also be disposed of in engineered structures or in rock caverns at 50 – 200 m depth.

Engineered structures on or slightly below the surface is used for LLW in many countries, e.g. France, Russian Federation, UK and USA. LLW can also be disposed in rock caverns at 50-200 m depth, like in Sweden and Finland, or even in mined tunnels at 400 -1000m depth, like in Canada or Germany.

ILW and SNF will be disposed in rock caverns or tunnels at 400 – 1000 m. If the quantities are small and the content of long lived radioactivity is low ILW can be disposed of at less depth. This is e.g. planned in Finland.

In the end the choice of disposal alternative will be determined by the possibilities to fulfil and prove the long term safety requirements. Given the long time perspectives to be considered, several hundred to several hundred thousand years, depending of type of waste, the safety can only be shown by a stringent and scientifically based safety assessment.

The geological conditions are different in different countries. Thus, disposal at depth in tunnels or caverns is practiced in different geological settings. In Sweden and Finland disposal is performed in crystalline rock. In France disposal in clay rock is planned for ILW and HLW. In Switzerland clay rock disposal is considered for all types of RW. In Germany disposal in salt rock was the prime option until a few years ago. Now a wider search is ongoing in which several different rock types are considered. The same is the situation in the US, where a repository for HLW and SNF was planned in volcanic rock, but now a wider search is ongoing. ILW is disposed in salt rock in the US.

8.2 Disposal of VLLW

Very low level waste (VLLW) is defined as:

> Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control.

In some cases, like in Sweden, disposal facilities for VLLW have been built at the sites of the NPPs (Figure 8-1), and will subsequently also be used during the dismantling of the NPP. The waste to be disposed must have such a low activity concentration that it could be freely released within 30 years. A similar facility has just been licensed in Finland.

Figure 8-1. Disposal of VLLW at the Oskarshamn NPP in Sweden.

In other cases, e.g. France and Spain, a centralized VLLW disposal facility has been built as shallow trenches with engineered covers. An example of such a disposal facility is Morvilliers in France (Figure 8-2) [Andra, 2021]. The waste is mainly protected by a cover with low permeability (Figure 8-3).

Figure 8-2. Disposal of VLLW waste at the special disposal facility for such waste at Morvilliers, France. (Courtesy of Andra)

In other countries, which do not have special disposal facilities for VLLW, the VLLW is disposed of together with other waste types, mainly LLW. The decision on disposal method is usually made on economic and regulatory grounds.

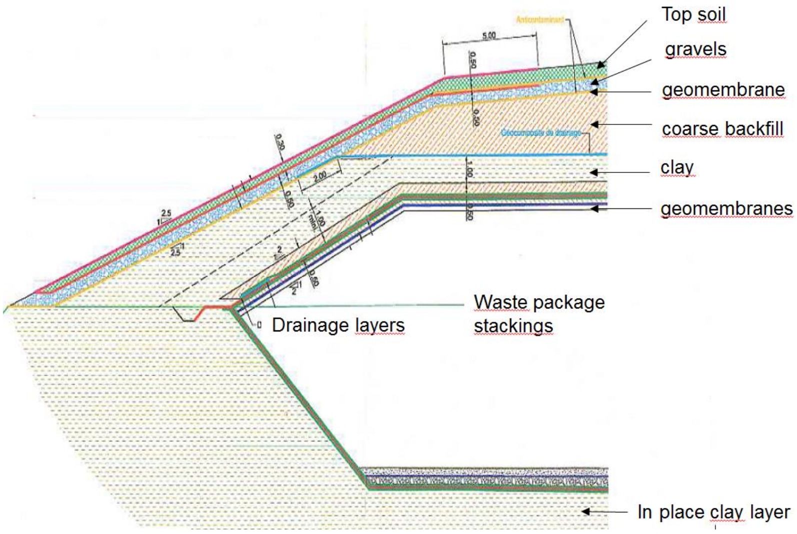


Figure 8-3. Cross section of VLLW disposal facility at Morvilliers, showing the different barriers in the cover.

8.3 Disposal of LLW

LLW is defined as:

> RW with only limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities.

Disposal facilities for LLW are in operation since more than 40 years in several countries around the world. These include facilities built on or near the surface, or facilities built in specially excavated rock caverns. The surface facilities are the most common and is used e.g. in France, Spain, USA, UK and Russian Federation, while rock caverns are used in Finland, Sweden, Hungary and Korea. Both types of facilities have been proven to be safe and fulfil the regulations of the country. In all cases the multiple barrier approach is being used to ensure long term containment of the radioactive elements. This means that the waste is surrounded by several different barriers to prevent leakage to the environment.

The choice of engineered near surface facilities or facilities in rock caverns is partly economic and partly based on public acceptance.

In most countries a national central facility for disposal of LLW is used, e.g. France, Germany and Sweden. In the USA several regional facilities are in operation, as it will be in the Russian Federation. Finland stands out as a special case as two disposal facilities have been built, one at each of the NPPs.

8.3.1 Surface facilities

Some of the earlier disposal facilities had a very simple design and the waste was essentially disposed of in trenches above the water table and with a watertight coverage, similar to a disposal facility for VLLW shown above. Over time the safety requirements have become more severe and thus the design of the facilities have developed. The modern disposal facilities have a more engineered design with several barriers against release.

Two examples of near surface engineered facilities are Centre de Stockage de l’Aube (CSA) in France (Figure 8-4) and El Cabril in Spain (Figure 8-5), which both have been in operation since the early 1990s. Similar facilities are in operation or under construction in several other countries, e.g. Slovakia, Japan, China and Belgium.

In CSA the disposal is made in large concrete structures (25 * 20 * 8 m) that are built on the surface. The conditioned waste packages are placed in the concrete structures and subsequently surrounded by concrete grout (Figure 8-6). When one concrete structure is filled a reinforced concrete lid is cast, including an impermeable cover. The disposal operations take place under a temporary roof that can be moved from disposal structure to disposal structure. Underneath the concrete structure there is a channel system for collection and control of any water that might come out of the structure. Each concrete structure can house about 3 500 m^3 of conditioned waste. It can be built and operated in a modular mode, such that the capacity is expanded as the need occurs. The licence and the corresponding safety assessment must, however, be based on the expected final size of the facility. The whole CSA site is designed for 1 000 000 m^3 [Andra, 2021]. The El Cabril facility as shown on Figure 8-5 can take about 40 000 m^3 [Enresa, 2021].

Figure 8-4. Aerial view of the Centre de l'Aube disposal facility for low-level waste in France. (Courtesy of Andra)

Figure 8-5. Aereal view of the El Cabril disposal facility in Spain. (Courtesy of Enresa)

Figure 8-6. Filling and grouting of waste compartments at CSA and El Cabril. (Courtesy of Andra and Enresa)

In Figure 8-7 a drawing of one module with 22 compartments, which can accommodate about 75 000 m^3 LLW at the CSA is shown.

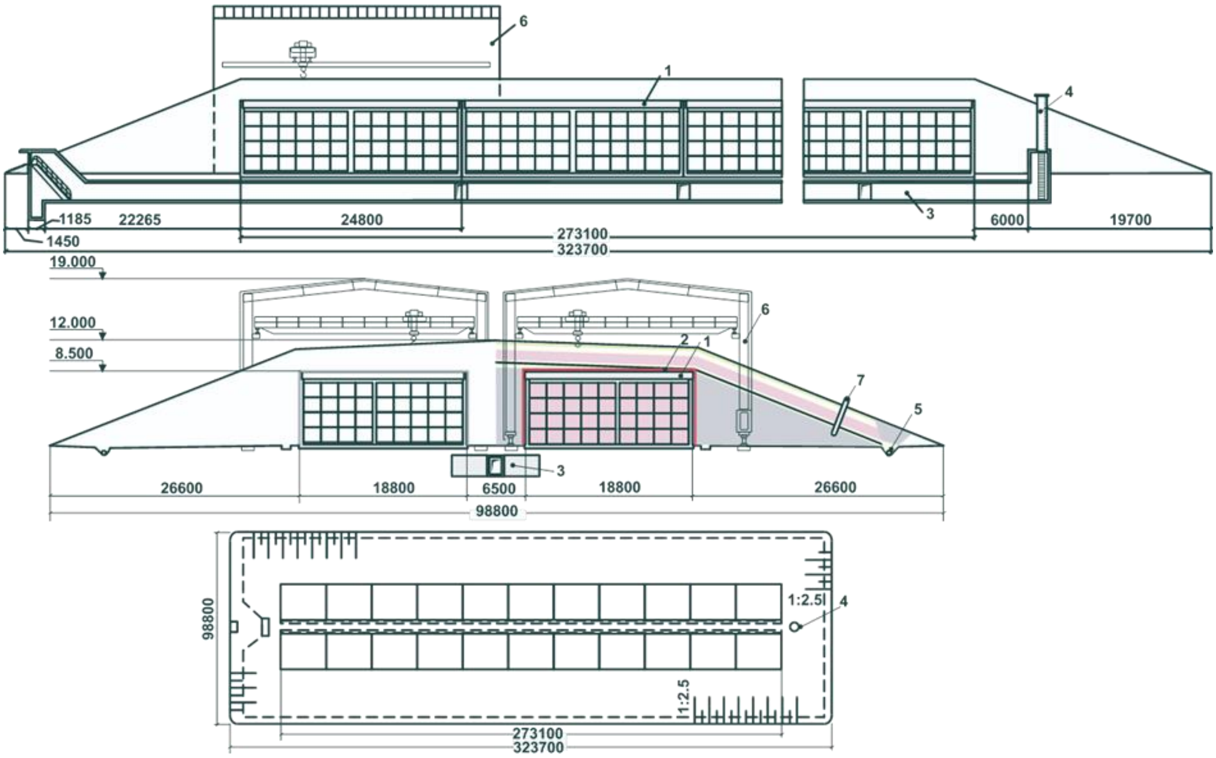


Figure 8-7. Drawing of a disposal facility for LLW with 22 disposal compartments.

After completion of the disposal the concrete structures will be covered by clay and earth and grass will grow on top of the mounds thus made. Figure 8-8 shows the closing of an older French disposal facility at the Centre de la Manche.

The site is intended to be surveyed, including control of any effluents, for at least 300 years, i.e. approximately ten half-lives for cesium-137 and strontium-90. The real long term safety of the disposal (>300 years) is then based on the low content of long lived radioelements, the characteristics of the waste form and packages, the watertight concrete structure and finally the surrounding geology.

A similar facility is being planned for Lithuania.

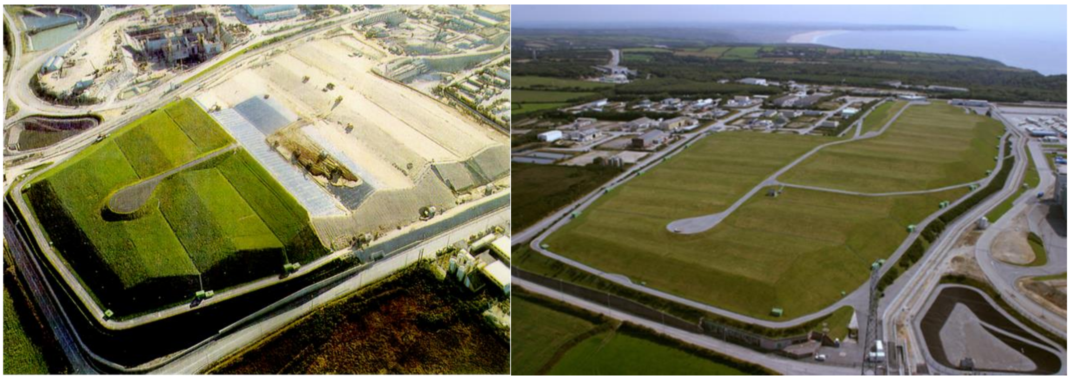
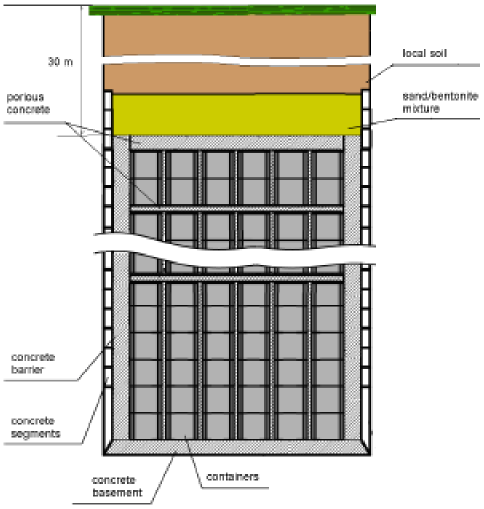


Figure 8-8. Aerial view of the Centre de la Manche disposal facility in France. The disposal facility has been closed and covered with clay and grass [Andra, 2021].

In earlier studies performed for Estonia an alternative design of a near surface repository has been proposed, which is an intermediary between an engineered surface facility and a deep facility [ALARA, 2015]. The design is shown schematically in Figure 8-9. It is a shaft type repository built from the surface. It will consist of a concrete cylinder, about 10 m in diameter, which is built at a depth of about 50 m and will be capped by 5 m of a mixture of sand and bentonite and covered with at least 30 m of soil. The waste will be filled in from the surface and the voids around the waste packages will be backfilled with a porous concrete. A similar concept is being considered in Slovenia.



Schematic cross section of a closed shaft type disposal facility

Figure 8-9. Conceptual design of near surface shaft repository [ALARA, 2015].

8.3.2 Disposal facilities in rock caverns

LLW disposal facilities in rock chambers at about 100 metres depth are in operation at Olkiluoto and Loviisa in Finland, at Forsmark in Sweden (SFR), at Gyeongju in Korea and at Bataapi in Hungary. In some countries disposal of LLW is planned at even greater depth, e.g. in Germany (Konrad) and Canada (Kinkardine).

Swedish disposal facility, SFR

In SFR the repository has been placed between 50 and 100 meter below ground level. It consists of several different rock chambers that have been adapted to the type and activity level of the waste (Figure 8-10). The SFR is built close to the Forsmark NPPs on the Swedish East Coast. The rock caverns for disposal are built underneath the sea bottom and are reached by two kilometre long tunnels.

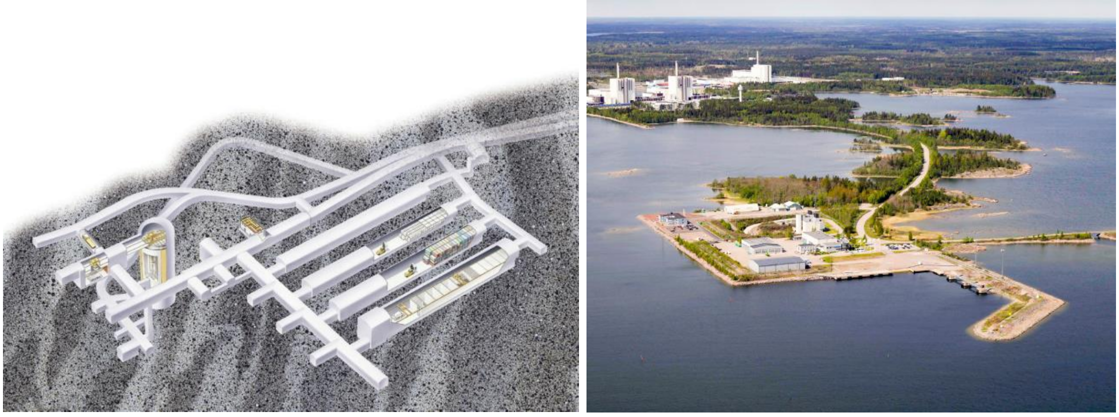


Figure 8-10. SFR LLW disposal facility at Forsmark Sweden with different types of rock chambers for different types of waste.

The most active LLW, mainly solidified ion exchange resins from the primary circuit of the reactors, is disposed in a large concrete silo (50 m high, 30 m diameter) and surrounded by concrete grout. Between the concrete silo wall and the rock a buffer of bentonite clay is introduced to further reduce any leakage. The multiple barriers are thus the waste form and package, the concrete structures, the bentonite clay and the rock (Figure 8-11).

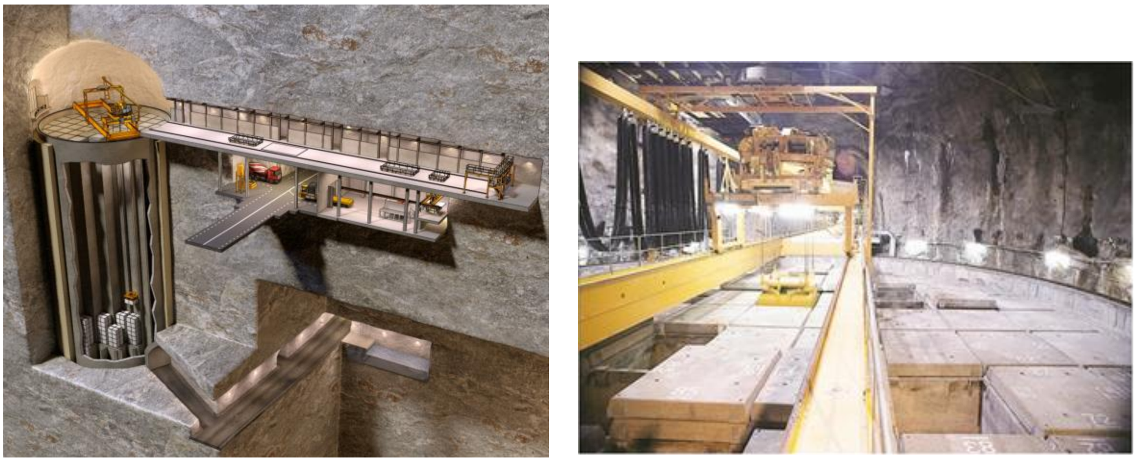


Figure 8-11. The silo for disposal of the most active LLW in SFR

For other waste simpler rock chambers have been built as shown in Figures 8-12 and 8-13. The facility has thus been adapted to the different types of waste and their very different activity content and surface dose rate. The accepted dose rate can vary between 10 mSv/h and 500 mSv/h. For the waste packages with the highest dose rate fully remote handling is utilised, while for the packages with a lower dose rate a forklift truck with some radiation shielding can be used.

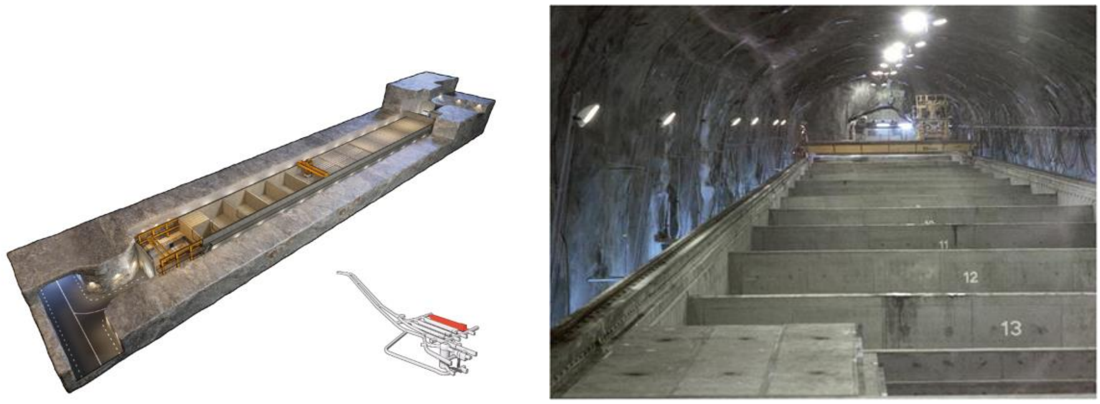


Figure 8-12. Rock chamber for LLW in SFR.

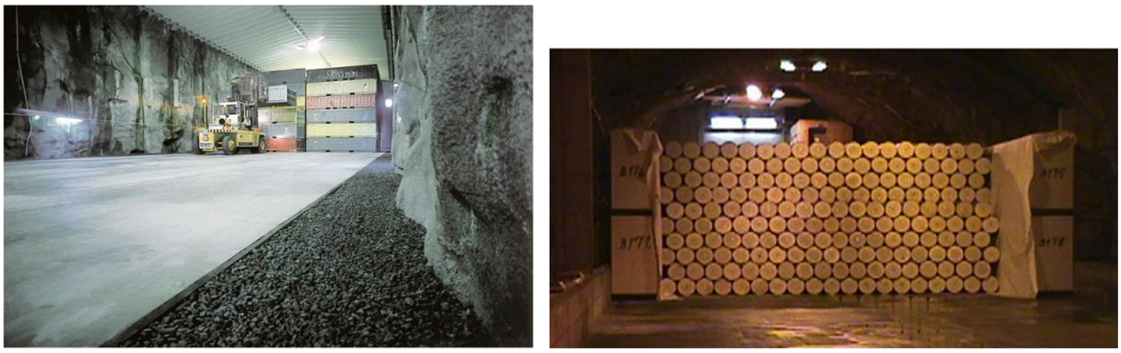


Figure 8-13. Rock chambers for LLW with low radiation level in SFR.

SFR can at present accommodate 60 000 m3 of waste from the operation of Sweden’s 12 reactors. An extension is under licensing to be able to accommodate also the decommissioning waste coming from the dismantling of the reactors.

When all waste has been disposed the tunnels will be closed and sealed and certain volumes around the more active waste backfilled. The facility has been built with the intention to make it possible to be abandoned without further surveillance once it has been filled. If this will happen in reality is of course a decision to be taken by future generations.

The amount of radionuclides that can be disposed of in SFR and in the different compartments is determined by the safety assessment and is regulated in the operating licence. For all waste types to be disposed a small safety assessment is performed to ensure that the waste will not deteriorate the barrier functions or exceed the radioactivity limit, a Waste Type Description.

Finnish disposal facilities for LLW

As mentioned before two separate disposal facilities for LLW have been built in Finland, one at Olkiluoto and one at Loviisa. The design of both is similar to SFR in Sweden, the difference being that in Olkiluoto only silos are used and in Loviisa only horizontal rock chambers. The two disposal facilities are shown in Figures 8-14 and 8-15 [Finland, 2020]

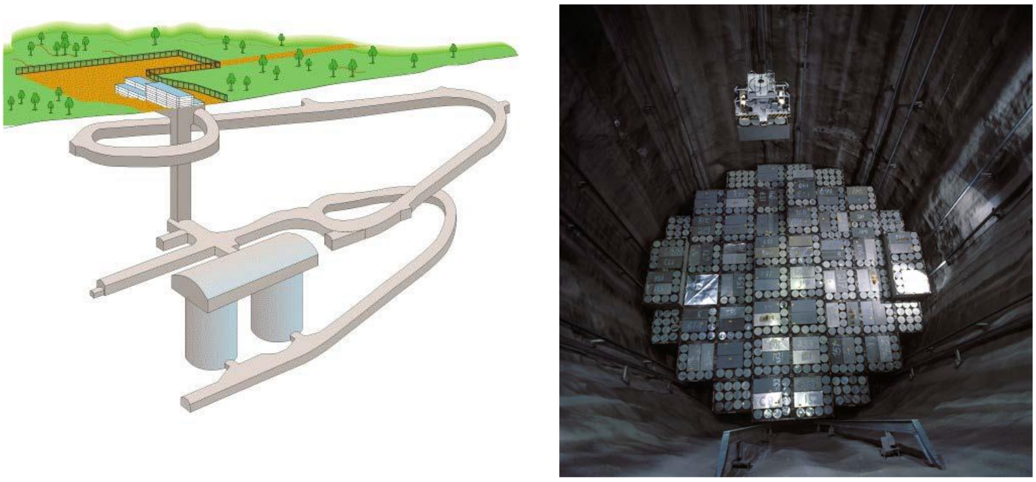


Figure 8-14. The Olkiluoto LLW disposal facility. Cross-sectional view of the facility (left) and LLW drums in the disposal silo (right). [Finland, 2020]

Figure 8-15. Loviisa LLW disposal facility. Cross-sectional view of the facility, including the planned extension for decommissioning waste (left) and, b) drums of LLW from reactor operation waste in the disposal hall (right). [Finland, 2020]

8.4 Disposal of ILW

ILW is defined as:

> Waste that, because of its content, particularly of long lived radionuclides, requires disposal at greater depths, of the order of tens of meters to a few hundred metres

The only licensed disposal facility for ILW is the Waste Isolation Pilot Plant (WIPP) in the USA where long lived, non-heat-generating waste from defence activities is disposed of in a geological repository built in salt beds.

Germany and Switzerland envisage that all LLW and ILW will be disposed of in one multipurpose, deep geological facility for non-heat generating RW, thus avoiding the need to separate waste containing short and long lived radionuclides before disposal. A facility for this waste is under construction at Konrad in Germany.

In France ILW will be disposed together with HLW in the planned facility Cigéo (Centre industriel de stockage géologique, industrial centre for geological disposal), for which a licence application is planned for 2022 (Figures 8-16 and 8-17). The facility will be built at about 500 m depth in an argillite clay formation [Andra, 2005].

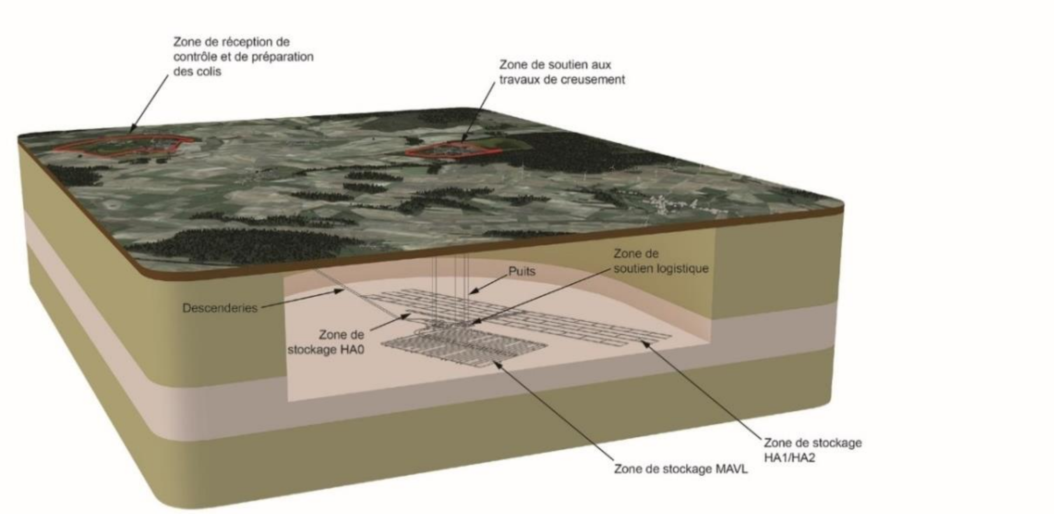


Figure 8-16. Layout of the Cigéo project for HLW and ILW geological disposal in an argillite clay formation in France. The ILW disposal is called Zone de stockage MAVL. (Courtesy of Andra)

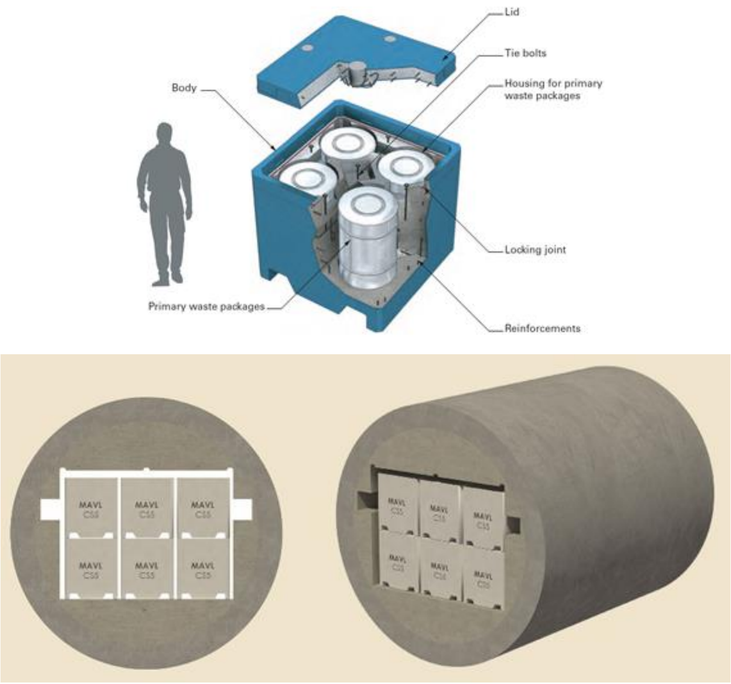


Figure 8-17. Planned disposal of ILW drums in tunnels at the Cigéo facility in France.

Sweden is considering to build a separate repository for ILW in crystalline around 2040, called SFL. The site has not yet been chosen. In the early safety assessments a design as shown in Figure 8-18 has been used. In Finland the repository for ILW is planned adjacent to the existing disposal facilities for LLW.

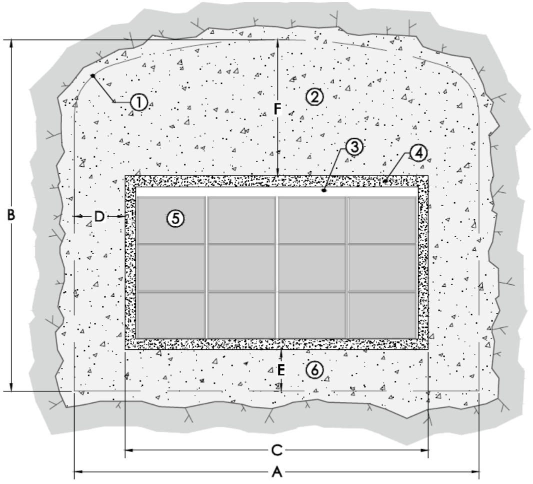


Figure 8-18. Cross-section of the disposal galleries in the SKB (Swedish) SFL concept in a rock chamber in crystalline rock 1) Gallery contour 2 and 3) grout 4) reinforced concrete, thickness: 0.5 m. Dimensions: A = 20 m, B = 17m.

8.5 Application to Estonia

8.5.1 Radioactive waste to be disposed of in Estonia

In this study primarily RW from the nuclear power plants planned to be built in Estonia is considered. The waste has been described in section 5. The total expected amount of VLLW and LLW is about 20 000 m^3. About two thirds of it will be generated during the 60 years of operation of the power plants, starting in 2035 and operating through 2110. The remaining one third will come from the subsequent decommissioning and dismantling of the reactors, preliminary foreseen for 2100 – 2125. Some of the decommissioning waste may be classified as ILW.

In addition, there is already existing low and intermediate level radioactive waste from earlier Soviet activities in Estonia, mainly from Paldiski, the disposal of which is the responsibility of A.L.A.R.A Ltd. (See section 9.2.2). The volume of this waste has been estimated to 3-4 000 m^3.

8.5.2 Alternatives for disposal of LLW from the NPPs

In deciding on a suitable alternative for disposal of LLW in Estonia several questions need to be considered:

- Will disposal in an engineered facility on the surface be acceptable from a regulatory and public acceptance point of view?
- Can suitable ground conditions for an engineered repository be found close to the planned nuclear power plant?
- If rock cavern disposal will be required, what geological conditions exist in Estonia for constructing stable rock caverns with a geology with low water transport? Do these geological conditions exist close to the planned nuclear power plant?
- Will also the waste from Paldiski, which is under the responsibility of A.L.A.R.A Ltd also be included in the LLW repository.
- When should a repository be available?

As most of the RW to be generated in Estonia will come from the future nuclear power plant, it would be advantages if the LLW repository could be located close to the power plant. This would reduce the needs for off-site transports and the operation of the repository could be integrated with the operation of the nuclear power plant. It also has the advantage that the local community accepting the nuclear power plant will see the advantages coming from nuclear power and thus the public acceptance for a repository could be expected to be easier than in other non-nuclear sites in Estonia. This corresponds to the choice made in Finland and Sweden, where the repositories have been built close to existing nuclear power plants. In Finland there is one repository at each of the reactor sites, while in Sweden a common repository for the four nuclear power plants have been built at one site close to the Forsmark nuclear power plant. The Swedish choice was made based on the fact that two of the sites for nuclear power plants did not have suitable geological conditions for building an underground disposal facility.

The choice between an engineered facility on the surface and a repository in a rock cavern is partly a technical/economic issue, partly a public acceptance issue. Of the neighbours to Estonia, the Russian Federation and Lithuania have chosen a surface facility, while Finland and Sweden have chosen rock cavern disposal facilities.

An engineered facility on the surface would make it easier to find a suitable site in the neighbourhood of the nuclear power plant as the requirements on the ground conditions are less restrictive. The safety of the repository is to a large extent dependent on the tightness of the engineered structure and the control of any drainage from the vaults. Only in the long term (> 300 years), when the institutional control has seized, could radioactive substances escape from the repository and the characteristics of the underground geology will be important. The activity level at this time will, however, be low.

An engineered facility on the surface of the design used in France would require less than 8 compartments and take an area of less than 15 000 m^2 to accommodate all LLW generated in Estonia under the scenario studied in this report

For a repository in rock caverns the main requirements will be that the geological medium has sufficient strength that rock caverns can be constructed. The size of the rock caverns will have to be adapted to the strength of the host rock. Another requirement is that the groundwater flow should be limited.

To accommodate all the LLW generated in Estonia 2 long rock chambers would be needed, to be able to segregate waste with higher radiation dose from waste with low dose.

Both in Sweden and Finland an early choice was made to build the repositories as rock caverns. This choice was based on the long-term experience of building underground facilities in the countries and the availability of good host rock at the sites of the power plants. It was also considered at the time that it would not be acceptable from a public view to build engineered surface repositories.

In the reasoning above it has been considered advantageous if a LLW repository could be built close to the nuclear power plant. This doesn’t exclude that it will be necessary to first perform a wider siting activity, including a study of possible locations all over Estonia, taking into account inter alia geological conditions, industrial infrastructure, transport issues and public acceptance issues. This is required for the Environmental Impact Assessment (EIA). Such an exercise might point out that some other area has clear advantages and should be chosen. The study might also show that it will not be possible to construct a repository close to the nuclear power plant and thus another site will be needed, e.g. close to the Paldiski site as mentioned in the earlier study mentioned above [Esoniat, 2015].

The inclusion or not of the legacy waste from Paldiski is a political/commercial rather than a technical issue. If these wastes are properly conditioned and characterised it should be possible to include them among the waste from the nuclear power plant. In Sweden it was early decided that the SFR repository, and later the SFL repository should also accommodate, against compensation, the waste from the Studsvik research facility. This is also the case for the VLJ repository at Olkiluoto in Finland.

The timing of the repository will have to be determined. Unlike for the SNF there is no need from an optimisation point of view to delay the disposal. An early start of the repository would mean that the conditioned waste can be disposed soon after its generation, thus avoiding the need for large interim waste storage facilities. Some buffer storage facilities will, however, always be needed. This is the approach taken in Sweden and Finland where the disposal facilities were taken into operation within 15 years after start of power operation. Given the rather small volumes of waste to be generated in Estonia and the fact that a lot of the waste will be generated during the decommissioning and dismantling of the reactors might indicate that it would be more efficient and less costly to delay the repository until this period. This could, however, generate a bad public image that the waste issues are not properly taken care of. This was one reason why Sweden and Finland choose to start disposal early.

8.5.3 Disposal of VLLW

The requirements on a disposal facility for VLLW is less stringent than for LLW given the much lower content of radioactive substances. The VLLW can thus be disposed in simple landfill arrangements. Alternatively. the VLLW could be disposed in the same repository as the LLW, but with less engineered barriers. This is the approach taken in Finland, while in Sweden some VLLW is disposed in simple landfills at some of the nuclear power plants, thus relieving disposal space, and some is disposed of in a simplified way in a rock chamber in SFR. Recently it was decided that also in Finland a VLLW disposal facility will be built at Olkiluoto.

Which solution will be made for Estonia will be a question of optimisation. For the case that the repository for LLW is delayed it might anyhow be advantageous to have a simple land fill disposal facility for VLLW to avoid occupying storage space and limiting the requirements on the stability of the waste packages.

8.5.4 Disposal of ILW

Only limited volumes of ILW will be generated during the operation of the reactors. This ILW will be packaged in shielded boxes and stored together with the LLW. Most of the ILW, a total of 1 000 m^3 will come from the dismantling of the reactors.

Depending on the total activity content in the ILW it might be possible to accommodate it together with the LLW, especially in the case of rock caverns. Otherwise, it will be necessary to build a separate deep repository for these wastes. In Finland it is considered possible to dispose of the ILW together with the LLW, while in Sweden, which has more reactors and also a substantial amount of ILW from earlier nuclear research activities, it has been necessary to plan for a separate deep facility, SFL.

If a separate ILW facility will be needed it should preferably be connected to the repository for SNF, If the volumes of ILW are small it might even be efficient to use the same type of waste canisters as for the SNF.

9 Organizational structure for the management of radioactive waste

9.1 Organization of RW management - International overview

The importance of a safe and effective SNF and RW management is reflected in the Joint Convention on the safety of spent fuel management and the safety of radioactive waste management [IAEA, 1997], which entered into force in 2001, It is the only international, legally binding instrument on this type of waste. The objectives of the Joint Convention are:

- to achieve and maintain a high level of safety worldwide in spent fuel and radioactive waste management, through the enhancement of national measures and international co-operation, including where appropriate, safety-related technical co-operation
- to ensure that during all stages of spent fuel and radioactive waste management there are effective defences against potential hazards so that individuals, society and the environment are protected from harmful effects of ionizing radiation, now and in the future, in such a way that the needs and aspirations of the present generation are met without compromising the ability of future generations to meet their needs and aspirations
- to prevent accidents with radiological consequences and to mitigate their consequences should they occur during any stage of spent fuel or radioactive waste management.

In the implementation of the Joint Convention strong emphasis is put on the legal and other rules and on the organization of the work.

Although the Joint Convention clearly states that the State has the overall responsibility to ensure that the RW is safely handled and disposed of, the way the State fulfils this responsibility is organised differently in different countries. It is useful to distinguish between the practical responsibility for handling the waste and the long term responsibility for disposal of the waste.

In accordance with different IAEA documents the owner or licence holder of a facility, e.g. a nuclear reactor or a waste management facility, has the practical responsibility for safe handling of the material. The fulfilment of this responsibility is supervised by the national regulatory authority.

When it comes to the long term responsibility other aspects also need to be considered. Many States have created national radioactive Waste Management Organizations (WMOs) that are responsible for developing arrangements for disposal of SNF and RW. In some countries the WMO is a State owned organization, while in others the WMO is owned by the waste producers, essentially the companies operating nuclear power plants. In any case the real long term responsibility for closed repositories will always lie with the State.

The WMOs may also be responsible for waste processing and interim storage and for the centralized collection and management of SNF and RW. Detailed information about the present situation world wide can be found in [IAEA, 2017, Table A-2].

Most countries in the European Union have a dedicated WMO, but the tasks for the WMOs differ between the countries. They range from the WMO being responsible for the management of all waste outside of the NPPs or other facilities where RW is produced to the WMO just being responsible for the development, construction and operation of waste disposal facilities. Some WMOs are also responsible for the decommissioning and dismantling of the NPPs and other facilities.

The situation amongst the neighbouring countries to Estonia is as follows:

Finland: The two nuclear power companies TVO and Fortum have created a joint privately owned company Posiva Oy, which is responsible for the encapsulation and final disposal of SNF. They will probably also take care of some ILW, if needed. The responsibility for disposal of LLW and also for the decommissioning and dismantling of the reactors rests with each power company and these companies have consequently, as described, above built their own repositories at the two NPP sites.

Sweden: The owners of the NPPs have the full responsibility to manage and dispose of all RW coming from the NPPs. The NPPs are located at 4 different sites and owned by four separate companies. To manage and dispose of SNF and all RW, except some VLLW which is locally disposed, the four companies have created a joint company Svensk Kärnbränslehantering AB (SKB), which is responsible for managing all SNF and RW outside of the NPPs. At the NPP sites the responsibility lies with the NPP owner. This also includes the future decommissioning and dismantling of the reactors. SKB is thus responsible for transport of SNF and RW, interim storage of SNF and some ILW, and disposal of SNF and all types of RW. For LLW, SKB has built a central repository SFR at Forsmark in which all LLW generated in Sweden will be disposed. By a separate agreement SKB is also disposing of waste from the Studsvik nuclear research facility against payment.

Norway: Recently a state owned organization, Norsk Nuklear Dekommisjonering (NND), has been created to manage and dispose of all SNF and RW generated in Norway, emanating from the Norwegian nuclear research facilities.

Denmark: Like in Norway a state organization, Dansk Dekommissionering is being established.

Germany: All SNF and RW in Germany, outside of the NPPs, will be managed by an organization, Bundesgesellschaft für Endlagerung (BGE), owned by the Federal Government. The NPP owners has paid a one-time compensation to BGE to be relieved of their responsibilities for managing and disposing of the SNF and RW. This was part of a deal in connection with the phase out of nuclear power in Germany. Earlier there was a mixed responsibility between the power companies and the Federal State.

Poland: The organizational structure has not yet been determined. A State organization, Radioactive Waste Management Plant (RWMP), exists.

Lithuania: The responsibility for the management and disposal of all SNF and RW in Lithuania has been given to a state owned organization, Radioactive Waste Management Agency (RATA).

Russian Federation: The disposal of LLW is performed by a state owned organization, National Operator for Radioactive Waste Management (NO RAO).

In summary, it can be seen that different organizational structures for the management of SNF and RW have been created in different countries. This is an effect of different national traditions, specific political choices, and the size of the nuclear power system. The most common organization is that a centralized state controlled organization has been set up. However, in several countries and notably in Sweden and Finland the responsibility for implementing the necessary disposal facilities have for practical and political reasons been given to the owners of the NPPs, which include both private and state owned companies. In some countries, e.g. in the USA, also purely commercial private companies have been established, which are dedicated to disposal of LLW and which have no connection to power companies. No such disposal company exist in Europe.

9.2 Proposed organization in Estonia

9.2.1 General structure

The main players involved in radioactive waste management are the waste producers, the waste disposer (WMO) and the nuclear regulator. Their relation is often described as a triangle (See Figure 9-1).

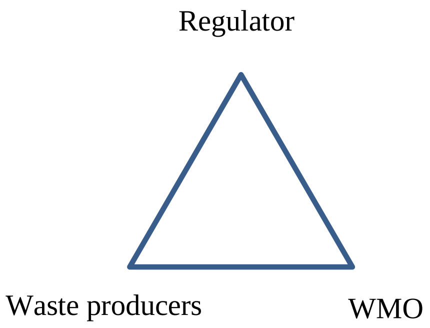


Figure 9-1. Relation between regulator and implementors for radioactive waste management. The regulator should always be independent of the implementers, while the waste producers and the WMO could either be totally separated or part of the same organization.

In accordance with international recommendations, e.g. IAEA Safety Standards [IAEA, 2006] and the European Directive on the responsible and safe management of spent fuel and radioactive waste [Euratom, 2011], it is important to distinguish between the role of the regulator and the role of the implementer of the waste management activities, and to ensure the independence of the regulator. The regulatory responsibility in Estonia lies with the Ministry of the Environment through the Environmental Board and the Environmental Inspectorate, while the existing implementing body at present reports to the Ministry of Economic Affairs and Communications [Estonia, 2017]. An alternative could in the future be that the implementer is a private company as discussed in the following. The organization of the regulator is not further discussed in this report.

In several countries it is also considered important to distinguish between the roles of the waste generator and the waste disposer. This is not the case in Sweden and Finland and based on this experience such a distinction is not considered to be of importance for Estonia.

9.2.2 Existing organization

To take care of the RW remaining in Estonia from past nuclear activities performed by the Soviet Union, a state owned company A.L.A.R.A. Ltd has been created. A.L.A.R.A. Ltd reports to the Ministry of Economic Affairs and Communications [Estonia, 2017]. A.L.A.R.A is responsible for

- the management and decommissioning of the Paldiski former nuclear site and Tammiku radioactive waste storage;
- the management and storage of RW generated in Estonia;
- the development and implementation of radioactive waste management projects;
- the provision of services in the fields of radioactivity and radioactive contamination measurement and radioactive contamination deactivation;

- the development and implementation of plans for the conservation and safe dismantling of unnecessary and/or hazardous establishments of Paldiski former nuclear facility.

At Paldiski A.L.A.R.A receives RW, mainly disused sealed radiation sources, from different institutions in Estonia. It also provides transport services for the RW.

A.L.A.R.A is further leading the planning and implementation of a disposal facility for the legacy waste. According to the national policy this should be established by 2040 [Estonia, 2015]

9.2.3 Alternatives for a future organization

With the establishment of nuclear power plants in Estonia the situation concerning generation and management of RW in Estonia will change substantially. The most important changes are:

- Spent nuclear fuel will be generated and will have to be stored and subsequently disposed of deep underground. Alternatively, the fuel will be reprocessed abroad and the residues, HLW and ILW, will have to be disposed of deep underground.
- LLW in larger quantities will be generated at the NPPs and will need treatment, conditioning, packaging at the NPPs and subsequent disposal in an LLW disposal facility.
- Substantial volumes of LLW and some ILW will be generated during the decommissioning and dismantling of the reactors.

Although the management of the SNF is not the subject of this report it should also be considered in the context of the future organization for the management and disposal of LLW and ILW.

In principle three alternatives can be seen for the future organization:

1. The State takes the responsibility for developing and implementing disposal facilities for all types of waste. This means that A.L.A.R.A, or a successor of A.L.A.R.A, gets a broader mandate to prepare for the disposal of all types of RW in Estonia and to arrange for interim storage as necessary.
2. The power company takes the responsibility for management and disposal of LLW, while the State takes the responsibility for disposal of SNF and ILW.
3. The power company is given the responsibility to manage and dispose of all types of RW from the NPPs. This can be given as a requirement to obtain the operating licence for the NPPs, written into the law as it is done in Sweden.

In the long term after closure of the disposal facility, of course, the State will have to take over the responsibility in all alternatives. In all alternatives it can further be assumed that the power company will have to pay all costs for the management and disposal, either directly or through payments to the State.

The first alternative, full State responsibility for disposal, is the one that is used in most countries. It has the advantage of clarifying that the State sees the introduction of nuclear power as a beneficial activity and that it acknowledges that the long term responsibility lies with the State. It also means that the power company can concentrate on its prime business, to generate electricity. It has the disadvantage that the development of disposal facilities and the associated costs, and thus the impact on the electricity price will be outside the control of the power companies. It might also have a negative impact on the public acceptance of nuclear power, as the waste producer do not take full responsibility for managing its waste.

The second alternative, split responsibility between the power company and the State, has the advantage that the power company remains in full control of implementation and costs of disposal of LLW. This advantage is even greater if the disposal facility can be located on or close to the premises of the NPP. In that case the disposal activities can be fully integrated with the operation of the NPP, thus minimising the need for on-site storage and optimising the use of operation staff during periods of lower maintenance activity, as is done at the Finish NPPs. For the SNF, the disposal of which comes much later, possibly after the reactors have been stopped, the advantages and disadvantages given for the first alternative remain.

A variant of the second alternative is applied in some countries, e.g. the USA, where LLW is disposed by specialised companies, while the State through the Department of Energy takes responsibility for storage and disposal of the SNF.

The third alternative is the one used in Sweden and Finland, where the power companies has been given the full responsibility to develop and implement all steps of the management from generation to disposal of the SNF and RW from the NPP s. As for the time being only one power company is foreseen to operate NPPs in Estonia the second option would mean that the full responsibility from generation to closed disposal could rest within one company. In Sweden, with four nuclear power companies, a fully owned subsidiary of the power companies has been created for the practical implementation, while the full responsibility rests with the power companies. In Finland, with two nuclear power companies, a fully owned subsidiary has been created in a similar way for the common disposal of SNF, while the disposal of LLW stays within the respective power company

The third alternative has the advantage that the power company has the full control of the implementation of the waste management activities and thus also the costs and the impact on the electricity price. It also means that the full chain from generation to disposal can be optimised within the company, e.g. concerning waste acceptance criteria in the different management steps. It further shows that the power company is taking the full responsibility for their activities. The disadvantage is that the waste management activities, especially the development and siting of a repository, are quite different from the operation of NPPs. It also has the disadvantage that the company will have to operate long after the power production has been stopped and the reactors have been dismantled.

9.2.4 Recommended organization for LLW management

Based on the experiences from Sweden and Finland it is recommended that the power company takes full responsibility for the management and disposal of LLW. This includes the treatment, conditioning, packaging and storage on site, as well as the development, siting, operation and closure of the LLW disposal facility. This model is particularly beneficial if the LLW disposal facility can be built on or near the premises of the NPPs, which opens up the possibility for real optimisation of the full chain from generation to disposal.

It could also be beneficial if this organisation also is given the responsibility, against economic compensation, for the disposal of the legacy LLW, which is now stored by A.L.A.R.A., as the volume of this waste is significantly smaller than the LLW from the NPP operation and decommissioning. This is the case in Sweden and Finland, where non-power reactor waste is disposed in SFR at Forsmark and in the VLJ facility at Olkiluoto

This proposal leaves the options open for the organisation of the responsibilities for the management of SNF and ILW, which require deep geological disposal, and which have a significantly longer time scale. In Sweden and Finland the nuclear power companies have been given also this responsibility and takes it through a separate company co-owned by the nuclear power companies in the country.

10 Financing radioactive waste disposal

10.1 Objectives

The time schedule for many of the activities connected to SNF and RW management is long and activities will continue several decades after the NPPs have stopped producing electricity and generate an income. This is particularly the case for the decommissioning and dismantling of the nuclear power plants and for the management and disposal of SNF or HLW as well as the waste from decommissioning. Substantial costs, which are a result of the nuclear power production, will thus occur long after the corresponding income has been generated. A funding and financing system has therefore been established in most countries. The objectives of the funding system are twofold:

- To ensure that financing will be available when the costs for SNF and RW management and for the decommissioning of the reactors occur, and
- To ensure that the costs for the nuclear electricity consider all costs connected to the production.

Funding systems based on the ‘polluter pays’ principle have been widely adopted. Most often funding is achieved by levying a fee on the kWh nuclear electricity produced. The fees are collected in funds, which should bear an interest to ensure the value of the funds to compensate e.g. to inflation.

A good modern overview of the funding systems in use in different countries is given in [NEA, 2021] and in [IAEA, 2020a].

In most countries the funding systems are set up to ensure the financing of the decommissioning and the disposal of SNF or HLW. For LLW from the operation of the NPPs quite often no specific funding system is set up and the costs for disposal is covered directly from the operational costs as they occur.

10.2 Financing of disposal of LLW from NPP operation

In most countries the disposal of LLW from the operation of the NPPs is performed soon after they have been generated and the costs thus appear while the NPPs are still in operation. In most cases these costs are thus seen as part of the normal operational costs for the NPP. As the actual cost for a disposal facility for LLW is normally quite front heavy, it is important to consider both the capital costs and the operational costs in an effective way.

One can distinguish three different financing methods used world wide for disposal of LLW:

- The investment of the disposal facility is seen as part of the investment of the NPP and thus capitalized and depreciated in the same way. Also the operational costs for the disposal is seen as part of the operational cost of the NPP. This is e.g. the approach in Finland.
- The waste is disposed of by a special company against a fee. The fee is seen as part of the operational costs of the NPP. This is e.g. the case in the USA.
- The costs for disposal of operational LLW is covered as part of the wider funding system for management of SNF and for decommissioning of the NPPs. A variant of this is used in Sweden.

The application of a funding system is described section 10.3.

10.3 Funding systems for the financing of long term liabilities for spent fuel and radioactive waste management

As this report also covers the management of LLW and ILW emanating from the decommissioning of the NPPs there is a need to also describe funding systems for the long term management costs. In this section an international overview is given and the challenges connected to long term funding systems are discussed. The discussion is applicable as well to the financing of decommissioning and the management of the spent fuel.

10.3.1 International overview

In most countries, the waste producers are responsible for the financing of all activities connected to the management and disposal of SNF (if it is regarded as waste) and RW and for the decommissioning of the facilities. Funding systems based on the ‘polluter pays’ principle have been widely adopted. Arrangements to ensure long term funding have been made. The arrangements differ from country to country and range from internal funds set aside in the balance sheet of a power company to funds completely controlled by the State, as part of the State budget. In most cases the funds are segregated from other activities and the content of the funds ear-marked for the specific purpose of SNF and RW management and for decommissioning. In the following some examples are given from different countries. More details can be found in [NEA, 2021 and IAEA, 2020a].

10.3.2 Examples of funding systems

Finland: The NPP owners are fully responsible for paying all costs connected to SNF and RW management and disposal as the costs occur. To ensure that adequate funding will be available, the nuclear operators have to contribute to the State Nuclear Waste Management Fund, which is a special-purpose fund independent of the state budget, existing under the administration of the Ministry of Economic Affairs and Employment of Finland (MEAE). In practice, it acts as a kind of guarantee fund from which potential remaining decommissioning and RW management measures are paid if a nuclear operator does not fulfil its waste management obligations.

The system is based on the requirement that at any moment there shall be sufficient funds available in the fund to cover the liabilities for remaining future decommissioning and SNF and RW management duties for the SNF and RW produced up to that moment. To this end the nuclear operators pay annual fees to cover their liabilities. In case of surpluses in the fund, the nuclear operators receive reimbursements. Part of the liabilities can be covered by securities provided by the nuclear operators, and they can borrow up to 75 % from the funds.

The remaining future costs are recalculated every three years at 0% discount rate.

Sweden: The NPP owners are fully responsible for paying all costs connected to SNF and RW management and disposal. A fee is levied on each kWh of nuclear electricity produced and put into interest bearing State controlled funds, one per power company. Even after a reactor has been shut down the utilities are obliged to pay fees if needed to achieve the necessary funding. The funds can be used for financing ongoing and future SNF and RW management activities. The fees are set individually for each power company and are adjusted every three years based on a new calculation of all remaining costs. In this calculation the future electricity production and the corresponding waste production is assumed. In setting the fees, based on the expected future electricity production, the costs are discounted using the expected future real rate of return.

In addition to paying the fee the NPP owners also have to provide guarantees for covering a situation when the funding is not enough, e.g. if the reactors are prematurely shut down, or the costs are underestimated.

Germany. Funding for SNF and RW management and for decommissioning has been set aside internally in the power companies. As of 2017 an agreement has been made that the Federal Government takes the full responsibility for management and disposal of SNF and RW outside of the NPPs and the German utilities have made a one-time payment to the Federal Government to cover the future costs. The payments have been made to a public external fund, which is managed professionally to ensure return of the invested money.

Decommissioning will still be financed from the company internal funds.

Lithuania: As no NPPs are in operation in Lithuania, the funding of the decommissioning of the old reactors and the management and disposal of the SNF and RW will have to be paid from the State budget. Also support has been given by foreign countries and organisations, e.g. the European Union and the European Bank for Reconstruction and Development.

Russian Federation: For SNF and RW produced since 2011 a special reserve fund has been set up and payments are made into the fund by the nuclear power producers. For SNF and RW produced before this date the costs will be covered by the State budget. Similar arrangements have been made for decommissioning.

France. Originally no funding was made as the costs would be covered from incomes generated during the late years of generation (similar to that the investments for the NPPs were covered during the early years of operation). Since several years now, however, funding is set aside in a segregated fund for each kWh produced. The ongoing activities of Andra, the organization responsible for disposal of all waste, are paid directly by the waste producers. The funding is thus only for future activities after the NPPs and other facilities have been shut down.

USA. The Federal Government, through the Department of Energy (US DOE) is responsible for transporting and disposing of SNF. Contracts have been established between the power companies and US DOE to the effect that DOE will accept the SNF generated and the companies shall pay a fee of 0,001 USD/kWh generated. If in the future there will be a need to change the fee it will only affect future electricity production. The fees are collected in a separate account in the Federal budget and can only be used for its purpose after appropriation by the Congress.

Disposal of low and intermediate level waste is paid directly from the power companies to commercial disposal companies. For the decommissioning the power companies are required to set aside funding in a segregated account, which can be used once the power company starts the decommissioning activities.

A more comprehensive overview of the financing and funding systems used in different countries is given in [IAEA, 2017, Table A–3, IAEA, 2020a, NEA, 2021]

10.3.3 Challenges

Given the long time perspectives, decades to centuries, over which the funding scheme should work there are a number of challenges connected to ensuring that a correct fee is levied and that the funding will be available when needed. Some of the more important challenges are:

- Cost calculations that span over several decades and the associated uncertainties
- Managing uncertainties in costs, future electricity production and future return on funds when setting the fees
- Managing the funds to ensure appropriate return
- Safeguarding the fund against external disturbances, e.g. cost increases, changing plans and schedules, and economic turbulence
- Final responsibility for payment in the case the funding is insufficient

These challenges are further discussed in Annex 2.

10.4 Application to Estonia

10.4.1 Proposed financing and funding system

To ensure that funding will be available to safely manage and dispose of SNF and RW from the future nuclear power production in Estonia it will be important to set up a solid and robust funding system. How this system will be managed will be a political decision. In any case it will require a supervision from the State to ensure its availability.

In the following a distinction is made for the financing of:

- Disposal of LLW from operation of the NPPs
- Decommissioning and management and disposal of LLW and ILW from dismantling, as well as ILW from operation
- Management and disposal of SNF.

For the latter two a funding system should be set up, such that funds for future financing are successively built based on contributions from the power production, through levies on the nuclear electricity generated or through another mechanism.

Also, the financing of the disposal of LLW from the operation of the NPPs could be covered by the funding system. Alternatively, these costs could be financed directly from the operation of the NPPs. The latter approach seems to be beneficial especially in the case, as proposed in section 9.2.4, that the power company takes the full responsibility for building and operating a disposal facility for LLW.

The following financing and funding approach is thus proposed to be applied in Estonia:

- Costs for disposal of LLW from operation of the NPPs are treated in the same way as the costs for operation of the NPPs, i.e. the investment is capitalized and depreciated over the operational time of the reactor and the cost for operation is part of the normal operation cost for the NPPs.
- A funding system is built to cover the future costs occurring after the reactors have been stopped. These includes costs for:
    - decommissioning the reactors
    - disposing LLW from the decommissioning operation
    - closing the LLW disposal facility (plus possible long term surveillance costs)
    - management and disposal of SNF and ILW (e.g. core components and reactor internals)
    - other activities such as R&D, regulatory oversight, public involvement, etc.
- The funding system is based on fees levied on the nuclear electricity production (EUR/kWh). The fees and the basis for the fees, i.e. future costs, electricity production and interest rates should be recalculated at regular intervals.
- The fund or funds should have an appropriate State oversight, e.g. as State controlled funds for the pension system, and be allowed to generate interest to at least compensate for inflation. Investments can be made in papers with low risk.

An important question is who takes the responsibility for any cost increase after the power production has stopped, the State or the nuclear power company. This is in the end a political decision.

When developing the Estonian financing and funding system the experience from the Swedish system, which has been working successfully for more than 30 years, can be utilised. This is briefly described in Annex 3.

11 Conclusions and recommendations

The nuclear power plant planned to be deployed by Fermi Energia OÜ in Estonia will, regardless of the specific technology used, produce RW throughout its operational lifetime and during the subsequent decommissioning. Different types of RW will be produced ranging from practically inactive very low level waste (VLLW) to spent nuclear fuel (SNF), which is highly radioactive and will require geological disposal at great depth. The largest volumes of waste will belong to the category of low level waste (LLW), which will need disposal in an engineered facility on the surface or in rock caverns below surface. Some intermediate level waste (ILW) will require disposal at similar depth as the spent fuel.

According to international guidelines and requirements it is the duty of a nation to develop a strategy for the management of RW and to identify the organisations responsible for the implementation of this strategy [IAEA, 1997, IAEA, 2009c, Euratom, 2011].

The purpose of this study, commissioned by Fermi Energia OÜ, is thus to describe and discuss alternative scenarios for managing VLLW, LLW and ILW from a future nuclear power plant in Estonia and identify one or more feasible strategies for safe, cost-efficient and robust waste management. The waste should come from the operation and subsequent decommissioning of up to 4 reactors with a combined capacity of 1200 MW_e to be commissioned in Estonia between 2035 and 2050 and operate for about 60 years.

In the assessment of the alternative strategies safety, economy and sustainability should be considered. Issues to be considered include organizational structure, description of waste streams for the type of reactors, management steps for different types of waste and financial model to support the strategy and implementation.

As no SMRs of the types considered for Estonia are yet in operation there is no direct experience to rely upon. However, as the technologies for most of the SMRs are similar to the existing NPPs with more than 50 years operating time, a lot of information can be gathered from this experience. This has been done in this report, in particular the experience gained in Sweden and Finland, but also from other countries worldwide.

In the preceding chapters the characteristics of LLW and ILW have been described and different means for treating, conditioning and packaging have been elaborated. Further different methods for storage, transport and disposal in use around the world has been described and analysed. In addition, alternatives for organisation of the implementation of the strategy and their funding has been discussed. On this basis some proposals for a strategy in Estonia is described in the following. It should be noted that the strategy for managing the SNF has not been part of this study. However, the conclusions of this study is closely connected to what is chosen as an SNF management strategy.

The situation in Estonia is particular as no NPP has yet been built, which provides a good opportunity for making an optimised planning already at this early stage.

A key finding of the study is that it is advantageous to consider the management and disposal of all types of waste to be generated already at the planning stage. This provides a possibility to design the treatment and conditioning methods in such a way that the whole system from generation to disposal can be optimised. This is particularly the case for LLW. It is thus important to consider possible options for the design and location of a disposal facility for LLW at an early stage.

Based on the presentations of international experience, especially from Sweden and Finland, given in this report the following recommendations can be given for the management of LLW:

- The responsibility for management and disposal of LLW should rest with the owners of the NPP.
- In connection with the siting of the NPPs, geological investigations should be performed concerning the possibilities to also build a safe disposal facility for LLW at the same premises or close to it.
- In parallel alternative possibilities should be studied as this will be needed for the Environmental Impact Assessment
- The choice between an underground rock cavern disposal or an engineered surface disposal will be based on the geological conditions on site and also take into account economic, political and public acceptance aspects.
- The required capacity will be about 15 – 25 000 m^3. About half of it will come from the decommissioning of the reactors.
- The disposal facility should preferably be operational within a few years after the start of operation of the first NPP. As the waste generation will span at least 80 years it might be advantageous to expand the disposal capacity in steps.
- It might also be advantageous to consider installing a simple disposal facility for VLLW on the site, as this will reduce the disposal volume needed for LLW and could simplify the treatment and conditioning methods at the NPPs.
- The choice of methods for treatment and conditioning of the RW from NPP operation should be based on the most modern technologies available, taking operational experiences, operational doses and long term safety in the disposal facility, as well as the costs into account. In particular, the compatibility between the waste and the disposal must be ensured.
- If no suitable site for a LLW disposal facility can be found at or close to the NPP site a wider search in Estonia will be required. This will involve considerable geotechnical, environmental, industrial, sociological and public acceptance activities as has been the case for the siting of the disposal facilities for SNF in Sweden and Finland.
- In this case the organisational structure might be different and the task could be given to a separate waste management organization (WMO), which also would be responsible for management and disposal of SNF and ILW.
- Based on the experiences in Sweden and Finland it could be efficient if the WMO is a daughter company of the NPP owner(s) or a direct part of the owner company, thus leaving the full responsibility with the NPP owners OÜ. The decision whether the WMO should be a State controlled organization or belong to the power company, however, is in the end a political decision to be taken in Estonia.
- The costs for disposal of the operational waste could be covered directly by the operational income from power production. A funding system will be needed for disposal of the decommissioning waste. This could preferably be coordinated with the funding system for SNF management and NPP decommissioning. Based on international experience the funding should be covered by a fee on the electricity production. The organisation of the funding system will need further considerations taking the specific Estonian circumstances into account.

The situation for the ILW, which will require deeper disposal, is slightly different as most of this waste will be generated during the decommissioning of the nuclear power plants. It might thus be advantageous to consider the disposal of ILW in connection with the disposal of SNF. This will require that some ILW from the operation of the NPPs and the existing ILW from earlier Soviet practices will have to be stored. These volumes are, however, small.

It should be noted that some of the recommendations given above are based on the experiences in Sweden and Finland and based on the legal system existing in these countries. It has not been the task of this study to analyse in what way this is in agreement with the specific legislation in Estonia. It is assumed that if the recommendations are in disagreement with the present legislation in Estonia, but found valuable, it will be possible to change the Estonian legislation taking into account the large change that the introduction of nuclear power will be and the possible need for other legal changes.

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Annex 1 – Small Modular Reactors Considered for Estonia

In this Annex information is provided about the four types of SMRs which are under consideration for Estonia. The information has been extracted from IAEA publications on the Advances in Small Modular Reactor Technology Developments, published annually [IAEA, 2020b, IAEA, 2018].

The SMRs described are:

- UK SMR. A 446 MW_e PWR developed by Rolls-Royce and Partners in the UK.
- NuScale. A 60 MW_e PWR developed by NuScale Power LLC in the USA.
- BWRX-300. A 300 MWe BWR developed by GE-Hitachi Nuclear Energy in the USA and Hitachi-GE Nuclear Energy in Japan.
- MMR^{TM}. A 5 MWe HTGR developed by Ultra Safe Nuclear Corporation in the USA.

Each of the reactor systems are briefly described in the following pages.

UK SMR (Rolls-Royce and Partners, United Kingdom)

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MAJOR TECHNICAL PARAMETERS

Parameter	Value
Technology developer, country of origin	Rolls-Royce and Partners, United Kingdom
Reactor type	3-loop PWR
Coolant/moderator	Light-water / Light-water
Thermal/electrical capacity, MW(t)/MW(e)	1276 / 443
Primary circulation	Forced (3 pumps)
Operating Pressure (primary/secondary), MPa	15.5 / 7.6
Core Inlet/Outlet Coolant Temperature (°C)	296 / 327
Fuel type/assembly array	UO_2 / 17x17 Square
Number of fuel assemblies in the core	121
Fuel enrichment (%)	4.95 (max)
Core Discharge Burnup (GWd/ton)	55 – 60
Refuelling Cycle (months)	18 – 24
Reactivity control mechanism	Rods and Gd_2O_3 solid burnable absorber
Approach to safety systems	Active and passive
Design life (years)	60
Plant footprint (m^2)	10 000
Site footprint (m^2)	40 000
RPV height/diameter (m)	11.3 / 4.5
RPV weight (metric tonnes)	220
Seismic Design (DBE)	> 0.3g
Fuel cycle requirements / Approach	Open cycle; Spent fuel transferred to a pool for storage prior to transfer to long term dry cask storage.
Distinguishing features	Modular approach facilitating rapid and cost-effective build.
Design status	Conceptual design

The design of the UK SMR is based on standard PWR components and the experience from operating existing PWRs. The layout of the plant is similar to standard PWR layout with the primary circuit, including reactor pressure vessel, reactor coolant pumps, steam generators and pressuriser inside a steel containment building and the turbine in an adjacent building. The pressure vessel is a bit smaller than a standard PWR pressure vessel.

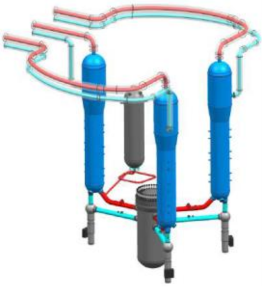

Figure A1-1. The three loop UK SMR showing the three steam generators (blue) with the reactor coolant pumps below and the reactor pressure vessel and the pressuriser (grey).

The fuel is a shorter version (2.8 m) of standard 17x17 PWR fuel. Contrary to standard PWR the UK SMR doesn’t use dissolved boron acid for critically control, but uses control rods and burnable absorbers (Gd_2O_3) in some fuel elements.

The approach to safety includes both passive and active safety systems. The passive systems are designed to deliver their safety functionality autonomously for 72 hours.

For more details of the UK SMR, please see [IAEA, 2020b pages 85 – 88].

NuScale (NuScale Power, LLC, United States of America)

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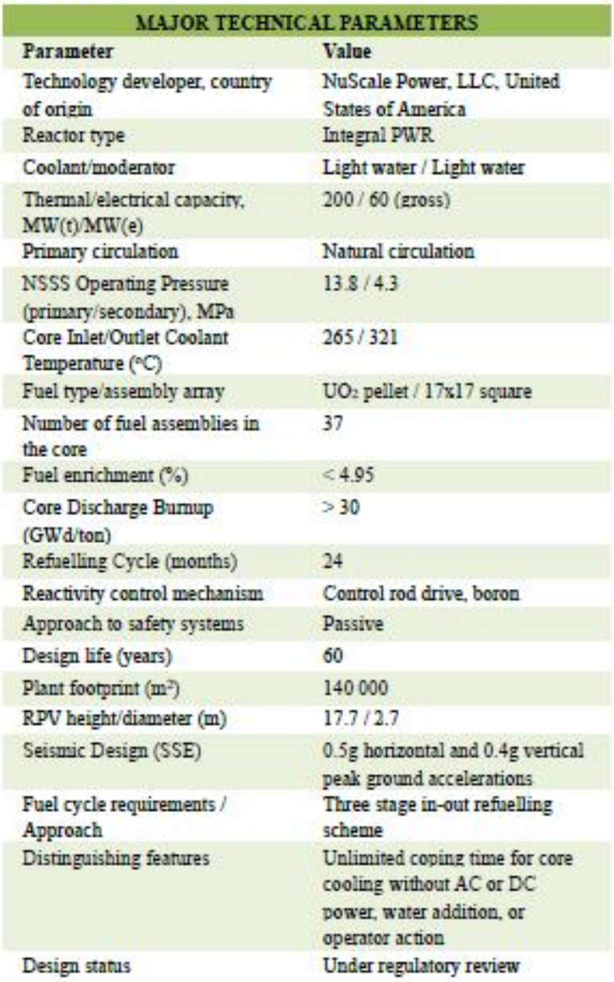

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	NuScale Power, LLC, United States of America
Reactor type	Integral PWR
Coolant/moderator	Light water / Light water
Thermal/electrical capacity, MW(t)/MW(e)	200 / 60 (gross)
Primary circulation	Natural circulation
NSSS Operating Pressure (primary/secondary), MPa	13.8 / 4.3
Core Inlet/Outlet Coolant Temperature (°C)	265 / 321
Fuel type/assembly array	UO_2 pellet / 17x17 square
Number of fuel assemblies in the core	37
Fuel enrichment (%)	< 4.95
Core Discharge Burnup (GWd/ton)	> 30
Refuelling Cycle (months)	24
Reactivity control mechanism	Control rod drive, boron
Approach to safety systems	Passive
Design life (years)	60
Plant footprint (m^2)	140 000
RPV height/diameter (m)	17.7 / 2.7
Seismic Design (SSE)	0.5g horizontal and 0.4g vertical peak ground accelerations
Fuel cycle requirements / Approach	Three stage in-out refuelling scheme
Distinguishing features	Unlimited coping time for core cooling without AC or DC power, water addition, or operator action
Design status	Under regulatory review

The NuScale Power ModuleTM (NPM) is a small, PWR. It is scalable and can be built to accommodate up to 12 modules of 60 MWe each in a single facility to meet the customer's energy demands. Each NPM is a self-contained module that operates independently of the other modules, but all modules are managed from a single control room.

The NPMs are placed in a common reactor pool. Each NPM consists of a cylindrical containment vessel that sits in the reactor pool structure (See Figure A1-2). The containment vessel incorporates the reactor core, helical coil steam generators and a pressuriser within a reactor pressure vessel. Each NPM is connected to a dedicated turbine-generator unit and balance of plant systems.

The Reactor Coolant System provides for the circulation of the primary coolant relying on natural circulation. No reactor coolant pumps are needed.

The fuel is a shorter version (about half height) of standard 17x17 PWR fuel. The fuel has burnable absorbers (Gd_2O_3). The criticality control is achieved through soluble boron acid in the primary coolant and control rods.

For more details of the NuScale SMR, please see [IAEA, 2020b pages 89 – 92].

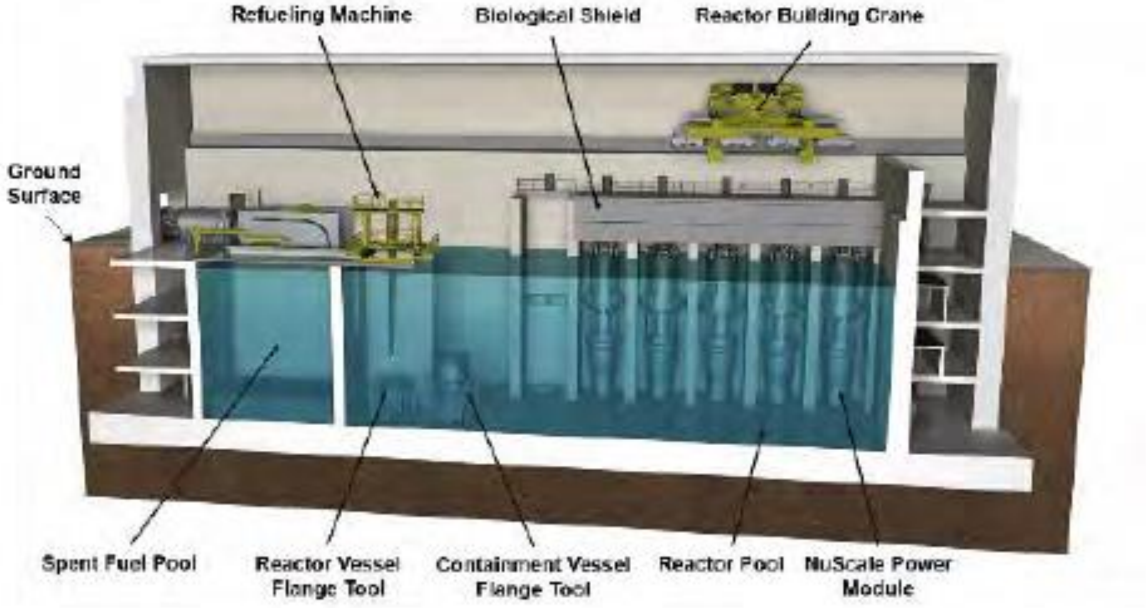

Figure A1-2. Cut away view of a NuScale SMR with five NuScale Power Modules.

BWRX-300 (GE-Hitachi Nuclear Energy, USA and Hitachi-GE Nuclear Energy, Japan)

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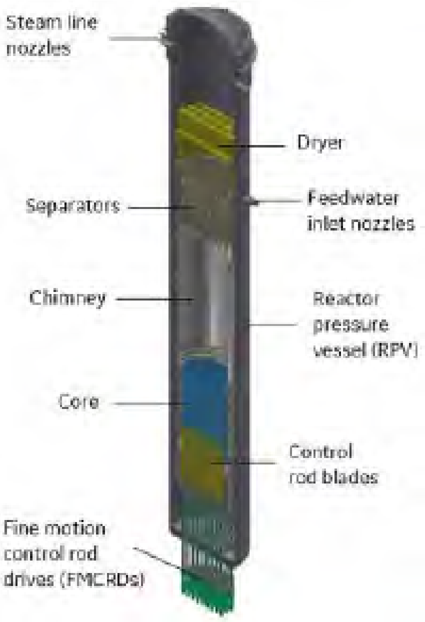

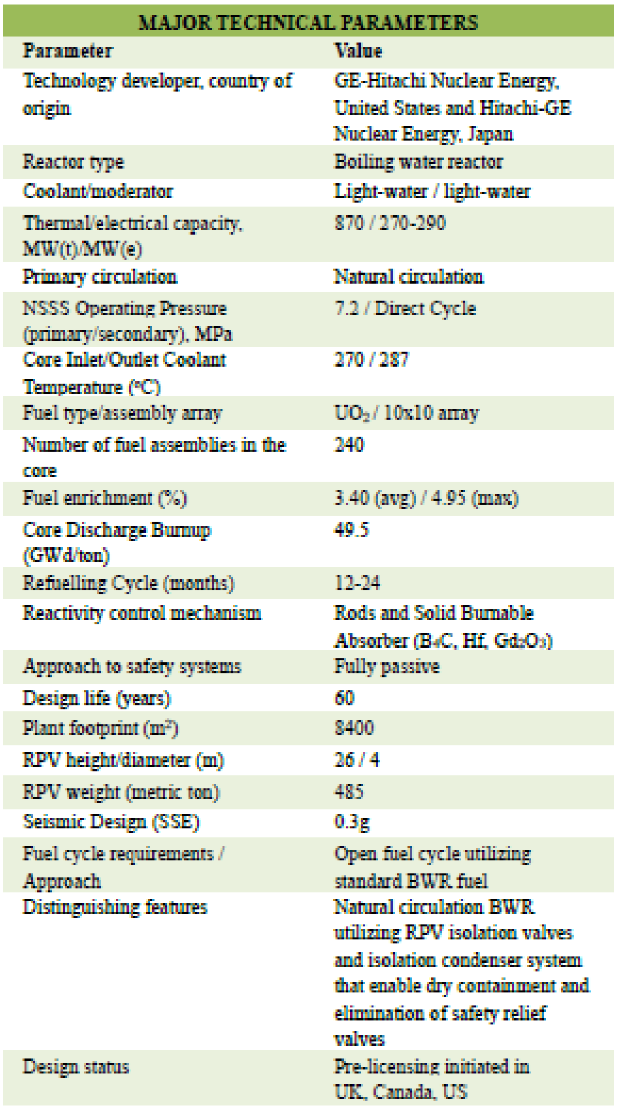

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	GE-Hitachi Nuclear Energy, United States and Hitachi-GE Nuclear Energy, Japan
Reactor type	Boiling water reactor
Coolant/moderator	Light-water / light-water
Thermal/electrical capacity, MW(t)/MW(e)	870 / 270-290
Primary circulation	Natural circulation
NSSS Operating Pressure (primary/secondary), MPa	7.2 / Direct Cycle
Core Inlet/Outlet Coolant Temperature (°C)	270 / 287
Fuel type/assembly array	UO_2 / 10x10 array
Number of fuel assemblies in the core	240
Fuel enrichment (%)	3.40 (avg) / 4.95 (max)
Core Discharge Burnup (GWd/ton)	49.5
Refuelling Cycle (months)	12-24
Reactivity control mechanism	Rods and Solid Burnable Absorber (B_4C, Hf, Gd_2O_3)
Approach to safety systems	Fully passive
Design life (years)	60
Plant footprint (m^2)	8400
RPV height/diameter (m)	26 / 4
RPV weight (metric ton)	485
Seismic Design (SSE)	0.3g
Fuel cycle requirements / Approach	Open fuel cycle utilizing standard BWR fuel
Distinguishing features	Natural circulation BWR utilizing RPV isolation valves and isolation condenser system that enable dry containment and elimination of safety relief valves
Design status	Pre-licensing initiated in UK, Canada, US

The BWRX-300 is a 300 MWe natural circulation BWR utilizing simple, natural phenomena driven safety systems. It is based on the design used for the ABWR in use in Japan and the ESBWR licensed, but not built in the USA.

The layout of the plant is similar to conventional BWRs with a reactor building and a turbine building and additional control and radwaste buildings (Figure A1-3). The reactor building contains all of the safety related components in the plant. The primary containment and the reactor pressure vessel are mostly below ground. In the reactor pressure vessel are the core, the chimney, the steam separators and steam driers. The chimney ensures that the reactor cooling water is circulated by natural convection and no circulation pumps are needed.

The fuel is standard GE full length fuel with 10x10 fuel pins. The reactivity is controlled by control rods and burnable neutron absorbers in the fuel.

The safety is built on the utilization of inherent margins (e.g. large water volumes) to accommodate transients. The safety systems are based on passive safety.

For more details of the BWRX-300 SMR, please see [IAEA, 2020b pages 93 – 96].

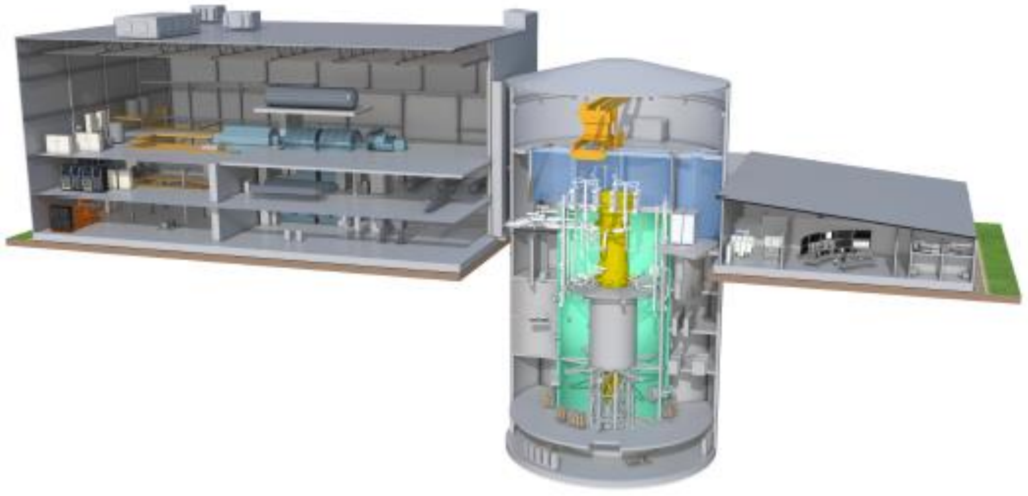

Figure A1-3. Cut away view of BWRX-300.

MMR^{TM} (Ultra Safe Nuclear Corporation, United States of America)

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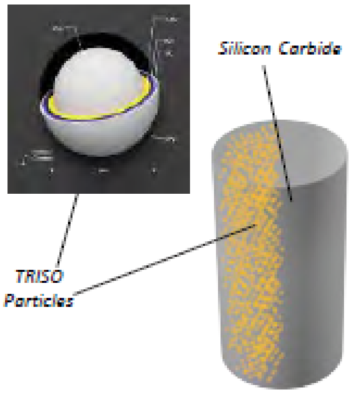
MMR Unit



Fully Ceramic Micro-encapsulated (FCM^{TM}) fuel

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	Ultra Safe Nuclear Corporation, USA
Reactor type	High Temperature Gas-cooled Reactor / micro-reactor / nuclear battery
Coolant/moderator	Helium / Graphite
Thermal/electrical capacity, MW(t)/MW(e)	15 / >5
Primary circulation	Forced circulation
NHSS Operating Pressure (primary/secondary), MPa	3MPa primary, 100kPa secondary
Core Inlet/Outlet Coolant Temperature (°C)	Helium 300 / 630, solar salt stored at 560
Fuel type/assembly array	FCM^{TM} or TRISO graphite /Hexagonal
Fuel enrichment (%)	HALEU 19.75%
Core Discharge Burnup (GWd/ton)	> 60
Refuelling Cycle (months)	Never; for the lifetime
Reactivity control mechanism	Control rod insertion, negative temperature coefficient.
Approach to safety systems	Passive (Category A), no moving parts, does not require fluid or natural convection
Design life (years)	20
Plant footprint (m^2)	130 x 96
RPV height/diameter (m)	8.1 / 3.1
Seismic Design (SSE)	0.3g
Fuel cycle requirements / Approach	Fueled once during lifetime.
Distinguishing features	No core meltdown; modular reactor and modular powerplant, adjacent non-nuclear power conversion plant; no EPZ required; load following / fully dispatchable; nuclear reactor isolated from load via molten salt loop; < 6 months assembly at site
Design status	Basic / Preliminary Design

MMR is quite different from the two other SMRs under consideration. It is a High Temperature Gas-Cooled Reactor (HTGR). The cooling medium is Helium.

The version of MMR described here is a very small reactor with 5 MWe output and is primarily foreseen for a small community.

The energy system consists of two plants, the Nuclear Plant and the Adjacent (non-nuclear) Plant. The Nuclear Plant provides process heat to the Adjacent Plant, where it is converted to electricity in a gas turbine.

The reactor core consists of hexagonal graphite blocks containing stacks pellets of Fuel Ceramic Micro-encapsulated fuel. The fuel in the pellets is so called TRISO particles with uranium and a cladding in a Silicon Carbide matrix.

The core has a low power density and a high heat capacity thus providing resilience against disturbances. In the case of an accident the heat passively dissipates into the environment without any moving parts, fluids or natural circulation. No active cooling or natural convection is required to maintain safe temperatures.

For more details of the MMR SMR, please see [IAEA, 2020b pages 303 – 306].

Annex 2 – Challenges in determining the funding needs for financing long term management of SNF and RW

Given the long time perspectives, decades to centuries, over which the funding scheme should work there are a number of challenges connected to ensuring that a correct fee is levied and that the funding will be available when needed. Some of the more important challenges are:

- Cost calculations that span over several decades and the associated uncertainties
- Managing uncertainties in costs, future electricity production and future return on funds when setting the fees
- Managing the funds to ensure appropriate return
- Safeguarding the fund against external disturbances, e.g. cost increases, changing plans and schedules, and economic turbulence
- Final responsibility for payment in the case the funding is insufficient

These challenges are briefly discussed in this Annex.

Cost calculations

As the activities and facilities needed to safely manage and dispose of SNF and RW in many cases will only be built and operated several decades in the future, the cost calculations will have to be performed for an assumed system, which inevitably introduces substantial uncertainties. At the time of cost calculation several decisions may still remain open, e.g. the geological media and the site for disposal facilities, and time schedule for the implementation.

For the purpose of the cost calculations, normally one or several scenarios are assumed for the future management of SNF and RW and the preliminary functions and designs of the necessary facilities are described, as well as other activities, e.g. R&D needs. The costs over time are then calculated as if the activities would be performed overnight now, i.e. in the present cost situation. Depending on the level of maturity of the scenarios appropriate contingencies will have to be added.

Another uncertainty is connected to the development of costs in the future. Not all costs will follow the general inflation. Some will increase faster than the inflation, while others will be slower. Typically engineering cost and other qualified cost increase faster than inflation as countries develop into a higher engineering status.

Given the uncertainties in the cost calculations and the successive evolution of the SNF and RW management systems most countries have found it prudent to update the cost calculations at regular intervals, e.g. every three to five years, and adjust the funding level accordingly.

Setting fees and handling uncertainties

In most countries fees are levied on the kWh nuclear electricity produced. Several factors are of importance in determining the appropriate fee. These include:

- Expected costs (as described above).
- Expected future electricity production, taking into account power plant availability and expected operational life time.
- Expected return on investment of the capital funded
- Level of security in the funding system

The basic idea is that the cost per kWh produced should be the same in constant money irrespective of when the kWh is produced. It will only change if the boundary conditions are changing, e.g. the estimated cost, the expected power production and the expected real rate of return on funded money.

The typical way of determining the fees is to ensure that the discounted future costs equals the future discounted fee payments plus the present fund content. In the discounting a typical real rate of return (after correction for inflation) is used. The level depends on the expected future development of the country and the expected fund management. Typically a value of 2 – 3 % has been used in many countries. At present lower values are used in Europe, reflecting the more pessimistic assumptions on future economic growth.

Another important factor is to what level of security the fees and the funds should cover even unexpected costs. Often an extra contingency is applied to safeguard against this. Alternatively, as is the case for Sweden, the fee should reflect the expected costs and unexpected costs are covered by guarantees from the NPP owners.

Fund management

A key question for management of the funds is the effective return on the funds and, in this connection, what investment possibilities exist. To safeguard against cost increases due to inflation and to keep the fees at an appropriately low level it is important that the fund content is invested in such a way that a proper return on the money is achieved. Given that the funds are really long term normally the flexibility in investments has in many countries been quite low, and restricted to very secure investments such as State or property bonds. In other cases a certain percentage of the funds could be invested in more profitable papers, such as shares. The possibilities and restrictions in the investment policy has a strong impact on the return of the funds, but they also influence the stability of the funds and the necessity of liquidity once the use of the funded money gets closer.

Safeguarding against disturbances

As the funds will exist for many decades the risk of disturbances are large. Such disturbances could include e.g. cost increases, time schedule changes, early reactor shut down, international and national economic turbulence, bad fund management and companies ceasing to exist.

As long as the waste producing activity generates a revenue it should be possible to adjust the funding requirements through relatively frequent recalculations of the future costs, incomes and return. This means that changes can be accommodated through a change of the levies on the future waste generation.

If the power production has ceased the situation is different. Then the risks will have to be born by future waste producers. This is e.g. the case in the US where a fee is levied per kWh produced and once the fee has been paid the State takes over the responsibility for the corresponding fuel. The risk from cost increases due to disturbances will thus be taken by the future production of nuclear electricity through increased fees and ultimately the Federal Government. Alternatively one could consider a system such as in and Sweden where the obligation to pay to the fund remains even after cessation of power production.

To ensure that money will be available in the long run some countries have introduced guarantees in addition to payment of fees.

Final responsibility for financing the implementation

Most funding systems are based on that the waste producer will pay all costs for the management of the waste produced, and that these costs will be taken from the funds that have been built up. This raises the question about what happens if the funds are insufficient, i.e. the funds are emptied before all activities have been completed.

Here the approaches are different in different countries. In some countries the State takes over the responsibility for covering unfunded costs, while in other countries the waste producer remains responsible for paying additional funding. In the latter case also the risk of insolvency of the waste producer has to be considered, which e.g. can be covered by guarantees as described above. In the extreme it will, however, always be the State which takes the final risk.

Annex 3 – The Swedish system for funding and financing the management of SNF and RW and the decommissioning of the NPPs

The basic principles for the financing of all activities connected to SNF and RW management in Sweden are set down in the Act on Nuclear Activities and in the Act on Financing of Residues from Nuclear Activities. They are:

- NPP owners remain liable for covering all costs until all waste has been disposed and the final repository has been sealed.
- To ensure availability of funding:
    - Fees are levied on all nuclear power production (SEK/kWh)
    - In case power production has ceased an annual fee can continue to be levied on the license holder (SEK/year)
    - The fees are collected in a State controlled fund. The fund is invested to carry an interest
    - Separate fees and accounts for each power company
    - The fees are based on a best estimate of the future costs for SNF and RW management and for reactor decommissioning and on an assumed future operation of the NPPs, set by law.
    - To cover early shut down of the reactors or unexpected cost increases or changes in the plans the NPP owners are requested to provide guarantees
    - The fees (and the guarantees) are adjusted every three years

The funded money can be used by the power companies and SKB to finance its activities, after approval by the regulator (SSM).

Cost and fee calculation

The fund should cover all future costs for management of SNF and RW outside of the NPPs and the decommissioning and dismantling of the reactors. As a basis for determining the appropriate fees for the future a cost calculation is performed by the NPPs through SKB every three years and reported to SSM in the so called Plan report [SKB, 2019]. The Plan report includes all remaining costs. SSM scrutinizes the cost calculations, makes its own judgement, and adds additional costs, e.g. regulatory costs and support to NGOs and local municipalities. Based on this and judgements on expected future electricity production and future return rate of the capital in the funds, SSM makes a proposal for the fees for each NPP owner to the Government. They also propose how large guarantees will be needed for early power plant close down and for unforeseen cost increases. Finally the Government decides on the fees and guarantees for the next three years.

One important assumption in determining the fees is the expected future operation of the reactors. Certain prudency has been applied in the fee calculations over the years. During the first several years the reactors were assumed, in the fee calculation, to be operated for 25 years. From 2006, when the earliest reactors had operated more than 25 years the fees were based on 40 years of operation (or at least 6 more years if you were getting close to 40 years), and as of 2018 it is based on 50 years of operation.

Fund administration

The fund is administered by a special Government body, The Nuclear Waste Fund (NWF). Until now NWF has only been allowed to invest in State and property bonds and in interest bearing accounts in the Swedish national bank. As of 2018 the NWF will be allowed to invest up to 40% of the capital in shares to increase the return on the capital.

Fund use

The funds are used for financing all activities in SNF and RW management outside of the NPPs and for the ongoing preparations for dismantling of the decommissioned reactors. The NPP owners thus request the needed financing for their own activities and for the activities of SKB from the NWF after approval by SSM. The Swedish funding model is shown schematically in Figure A3-1.

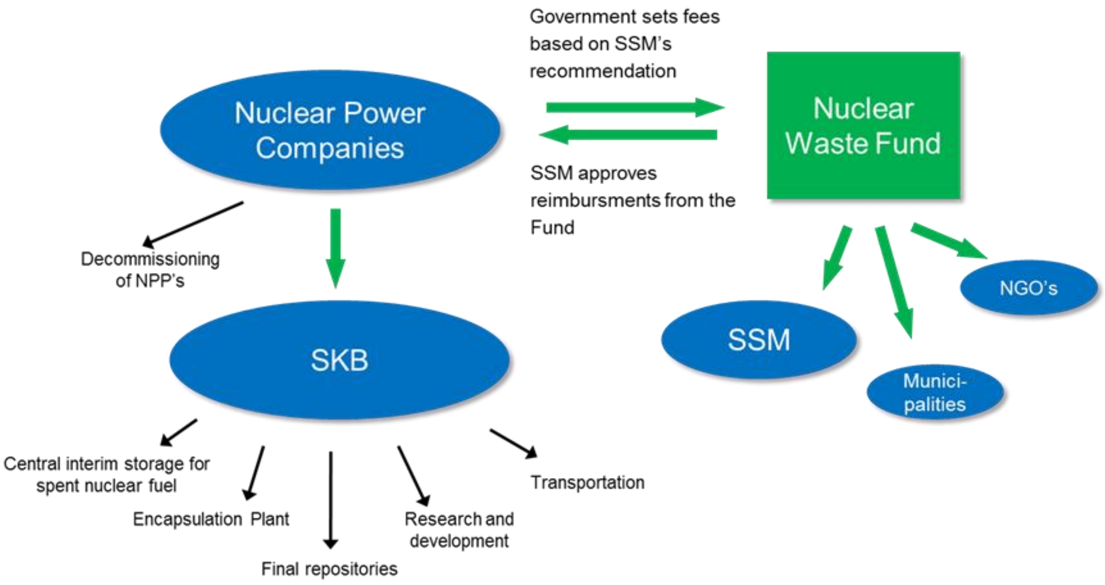


Figure A3-1. The Swedish model for funding of activities connected to SNF and RW management.

Guarantees

In addition to the fund build-up through fees extra stability of the financing system is obtained by the fact that the NPP owners have to provide guarantees to cover two different situations:

- An early shut down of the reactors, i.e. to cover the lack of funding as the reactors have not generated the expected electricity and thus not provided the expected funding.
- Unexpected cost increases. In the future also unexpectedly low real interest rates will be covered by this guarantee.

To calculate the need for guarantees for unexpected cost increases a statistical method is being used, which is based on a large number of possible disturbances and cost increases

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