School of Energy Systems
Degree program in Energy Technology - Nuclear Engineering

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Decommissioning and Final Disposal of Loviisa VVER-440 Reactor Pressure Vessel and its Internals

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Supervisor: D.Sc. (Tech.) Maria Leikola (Fortum Power and Heat Oy)
Lappeenranta: 19.10.2021

ABSTRACT

Lappeenranta-Lahti University of Technology LUT
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Decommissioning and Final Disposal of Loviisa VVER-440 Reactor Pressure Vessel and its Internals

Master's Thesis, 2021
93 pages, 27 figures, 15 tables, 2 appendices

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Keywords: Decommissioning, reactor pressure vessel, nuclear waste disposal, long-term safety, MCNP

Decommissioning of nuclear power plants is a challenging process in which the industrial decommissioning methods are combined with requirements of radiation protection and laws and regulations concerning the final disposal of nuclear wastes. The aim of nuclear decommissioning is to remove all the radioactive material from the facility, so that the facility can be cleared from the regulatory control. By default, all the removed material is classified as nuclear waste, which is required to be disposed of so that they will not cause unreasonable danger to the environment even during long time periods. Excluding nuclear fuel, the most activated components of a nuclear power plant are the reactor pressure vessel as well as its internals. In addition to the high activity the reactor pressure vessel is the single heaviest component to be handled during the decommissioning process.

To prepare for the required radiation protection measures the activity of the reactor pressure vessel as well as its internals is specified by using a MCNP-code, from which a nuclide specific activity inventory can be drafted. Based on this inventory the required radiation protection measures can then be designed by utilizing dose rate assessments made with the MCNP-code. Due to the high activity of the components in question, utilizing computerized models as a base of the designs is the safest and most cost-efficient way of working.

This master’s thesis will assess different decommissioning and disposal methods that can be utilized on the reactor pressure vessels of Loviisa nuclear power plant. According to the current decommissioning plan, the reactor pressure vessel and its internals will be decommissioned and disposed of as whole, so that the reactor pressure vessel would be utilized as a release barrier required by long-term safety. Internationally a more common way of decommissioning and disposing the reactor components is by segmenting and packing them to final disposal packages.

Based on the assessment, not a single optimal decommissioning and disposal method can be chosen, as different methods have their advantages as well as disadvantages. The master’s thesis is written for Fortum Power and Heat Plc and will serve as background material for updated decommissioning plan of the facility.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
School of Energy Systems
Energiatekniikan koulutusohjelma - Ydintekniikka

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Loviisan VVER-440 reaktoripaineastian ja sen sisäosien käytöstäpoisto sekä loppusijoittaminen

Diplomityö, 2021
93 sivua, 27 kuvaa, 15 taulukkoa, 2 liitettä

Tarkastaja: Professori TkT Juhani Hyvärinen
Ohjaaja: TkT Maria Leikola (Fortum Power and Heat Oy)

Hakusanat: Käytöstäpoisto, reaktoripaineastia, ydinjätteen loppusijoitus, pitkäaikaisturvallisuus, MCNP

Ydinvoimalaitosten käytöstäpoisto ja loppusijoittaminen on haastava prosessi, jossa yhdistyvät teolliset purkumenetelmät, tarkat säteilyturvallisuusvaatimukset sekä ydinjätteiden loppusijoittamista koskevat lait ja määräykset. Ydinvoimalaitosten käytöstäpoiston tavoitteena on poistaa laitoksista kaikki radioaktiivinen materiaali, niin että laitos voidaan vapauttaa ydinlaitoksia koskevasta valvonnasta. Lähtökohtaisesti kaikki poistettava materiaali luokitellaan ydinjätteeksi joka tulee loppusijoittaa, niin että siitä ei aiheudu kohtuutonta vaaraa ympäristölle pitkänkään ajanjakson kuluessa. Pois lukien käytetty ydinpolttoaine, ydinvoimalaitoksen aktivoituneimmat osat ovat reaktoripaineastia sekä reaktorin sisäosat. Aktiivisuutensa lisäksi reaktoripaineasti on myös painavin yksittäinen komponentti, joka käsitellään laitosta käytöstäpoistettaessa.

Jotta käytöstäpoistossa tarvittaviin säteilysuojelullisiin toimenpiteisiin voidaan varautua, reaktorin paineastian ja sen sisäosien aktiivisuus määritetään käyttäen MCNP-koodia. Koodilla aktivoituneille komponenteille luodaan nuklidikohtainen aktiivisuusinventaari. Inventaariin pohjaavat säteilysuojelulliset toimenpiteet voidaan tämän jälkeen suunnitella MCNP-koodilla tehtyjen annosnopeusarvioiden perusteella. Komponenttien korkeasta aktiivisuudesta johtuen tietokonepohjaisten mallinnusten käyttö on turvallisin ja kustannustehokkain tapa tehdä suunnitelmia.

Tässä työssä arvioidaan Loviisan ydinvoimalaitoksen reaktoripaineastioiden käytöstäpoistoon ja loppusijoittamiseen soveltuvia menetelmiä. Nykyisen suunnitelman mukaan käytöstäpoistetut reaktorikomponentit loppusijoitettaisiin kokonaisena, niin että reaktorin sisäosat sijoitettaisiin paineastian sisään, joka toimisi pitkäaikisturvallisuuden vaatimana vapautumisesteenä. Kansainvälisesti yleisempi tapa on kuitenkin paloitella ja pakata reaktorin komponentit loppusijoituspakkauksiin.

Arvioiduista käytöstäpoistomenetelmistä ei voida valita yksittäistä optimaalisinta menetelmää, vaan jokaisella menetelmällä on tarkastelun perusteella sekä positiivisia että negatiivisia tekijöitä. Tämä työ on tehty Fortum Power and Heat Oy:lle ja tulee toimimaan käytöstäpoistosuunnitelman taustamateriaalina.

ACKNOWLEDGEMENTS

I wish to express my gratitude to all my colleagues at Fortum for the support and guidance during this work. Special thanks go to Maria Leikola for supervising and providing helpful feedback for this work, Jussi-Matti Mäki for making the long-term simulations and helping me to understand them, Pasi Karvonen for helping me to understand the MCNP-code, and Pasi Kelokaski for offering me this interesting thesis topic.

My gratitude also goes to Professor Juhani Hyvärinen, for his encouragement, guidance and patience during this work. I am also grateful for great lectures and teaching I received at the LUT-university, especially from the Nuclear Engineering team.

Finally, I would like to thank my mother and aunt who fed me during my stay in the national landscapes of Koli, as the COVID-19 pandemic allowed me to work remotely in middle of these magnificent views.

Aapo Tommila
October 2021
Koli, Finland

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LIST OF SYMBOLS AND ABBREVIATIONS

Roman

A	Activity	[Bq]
m	Mass	[g]
M	Atom weight	[g/mol]
N_A	Avogadro constant	[1/mol]
$T_{½}$	Half-life	[a]

Greek

α	Mass fraction of the target element	[%]
β	Proportion of target isotope	[%]
λ	Decay constant	[1/a]
ν	Neutron speed	[eV, m/s]
Σ	Macroscopic cross section	[1/cm]
σ	Microscopic cross section	[barn, 10^{-24} cm^2]
ϕ	Neutron flux	[$1/cm^3$]

Abbreviations

ALARA	As Low As Reasonably Achievable
DWH	Decommissioning Waste Hall
IAEA	International Atomic Energy Agency
LANL	Los Alamos National Laboratory
LILW	Low- and Intermediate-Level Waste
NPP	Nuclear Power Plant
MCNP	Monte Carlo N-Particle code
MPS	Multipurpose Support Platform
ORNL	Oak Ridge National Laboratory
RSC	Radiation Shielding Cylinder

RPV	Reactor Pressure Vessel
RPVI	Reactor Pressure Vessel Internals
PTU	Protective Tube Unit
SPMT	Self-propelled Modular Transporter
STUK	Säteilyturvakeskus; Finnish Radiation and Nuclear Safety Authority
VVER	Vodo-vodyanoi Energetichesky Reaktor; Water-water Power Reactor

1 INTRODUCTION

Like all industrial facilities, nuclear power plants (NPP) must eventually be decommissioned when they reach the end of their operational lifetime. Early NPPs were designed to be operated for around 30 years, but in many occasions good maintenance policies and technical updates have increased the operating life time well beyond the original. However, eventually the maintenance of the facility will turn out to be uneconomical or political decisions dictate that the facility must be decommissioned. Decommissioning of NPPs pose some unique challenges when compared to traditional industrial decommissioning, as parts of the facility have been radiologically activated during the operation. Therefore, some of the traditional dismantling techniques are not applicable, and part of the decommissioning waste produced must be classified as nuclear waste which requires special disposal methods and facilities.

When a NPP is operating the materials surrounding the reactor core will be exposed to high neutron irradiation, which activates some of the stable elements present into radioactive isotopes. These unstable isotopes will in turn emit ionizing radiation that causes cell damage to living organisms. Consequently, radiation doses accumulated by the staff have to be taken into account during the decommissioning process and proper radiation protection measures must be taken. Reactor pressure vessel (RPV) containing the nuclear fuel where the chain reactions occur is in most cases the single largest, robust and activated component of a NPP. Therefore, it is one of the most challenging components to decommission and dispose of. This is mostly due to extremely high levels of radiation, which the size and weight of the components make even more challenging. In fact, parts of the reactor pressure vessel internals (RPVI) contain so high levels of activity that they cannot be dismantled without remotely operated equipment and the whole reactor hall must be evacuated from personnel while they are being processed or moved outside of the water filled reactor or storage locations.

As one could presume, NPP decommissioning is highly regulated by international and Finnish legislation when comparing to traditional industrial decommissioning. In Finland the supervisory authority is the Finnish Radiation and Nuclear Safety Authority (Säteilyturvakeskus - STUK), which defines the regulatory guides on nuclear safety and security, based on Finnish Nuclear Energy act 11.12.1987/990. These guides define the boundaries on how the decommissioning work must be performed and how the waste should be handled after dismantling has been completed. Major focus of the guides is on safety of workers and local population, aimed to minimize radiation doses of workers and the amount of radioactive waste produced, while also ensuring that radioactive emissions during the decommissioning process are kept as low as possible. (STUK, 2019)

Finland's first NPP was built on Hästholmen island in the municipality of Loviisa and it is currently owned and operated by Fortum, which is one of the major utility providers in Finland and Europe. Unit one (LO1) was connected to the grid in 1977 and unit two (LO2) in 1981. Both of the units were designed and supplied by the Soviet Union. Therefore, they are based on VVER-440 type pressurized water reactor design but have been modified to correspond with western safety standards. Originally the thermal power per unit was 1 375 MW, but plant modernization and optimized fuel loading patterns have increased this up to 1 500 MW per unit, from which 507 MWe of electricity is produced. Planned operating lifetime of the units was originally set for 30 years, while operating licenses were granted by the officials up to the year 2007. These operating licenses where then extended by 20 years in 2007, (Ministry of Economic Affairs and Employment of Finland, 2007) increasing the operational lifetime to 50 years. An environmental impact assessment of possibly increasing the operational lifetime for a further 20 years is currently underway. Current operating licenses are going to end in 2027 for unit one and in 2030 for unit two, after which both of the units are planned to be immediately decommissioned in case no further extension to the current operation license is granted or continuation of the operation is considered to be uneconomical.

While the actual facility decommissioning is still years away, Finnish regulatory guides oblige the operating license holder of the NPP to have a viable decommissioning plan for the facility. This plan has to be updated by the operating license holder and approved by the Ministry of Economic Affairs and Employment of Finland as well as STUK every sixth year (Act 11.12.1987/990). After the NPP has been permanently shut down a final approval of the decommissioning plan must be applied from authorities, before the decommissioning work can begin. The regulations also state that the decommissioning of the facility may not be postponed without a due cause, an internal research on this matter has been done and no such cause for Loviisa NPP was discovered, while economical viewpoints would also support the immediate decommissioning option (Kaisanlahti, 2018).

Decommissioning of the NPP is an extensive and complicated project, in which the RPV and RPVI are some of the most challenging components to decommission. This thesis will focus on the removal, dismantling and final disposal options of the Loviisa VVER-440 type RPV and RPVI. Decommissioning work planned for other parts of the facility will not be addressed, if clear connection to the RPV decommissioning cannot be seen. So far, three viable scenarios have been identified; final disposal of the RPV and RPVI without segmentation, segmenting and packaging of the RPV and RPVI, and segmenting and packaging of the RPVI while disposing the RPV as whole. The thesis will go through the fundamentals of nuclear decommissioning and radioactivity, after which the decommissioned components and their decommissioning and disposing process is addressed. Lastly the alternative options will be compared based on estimated schedules, economics, accumulated collective radiation doses and effects on long-term safety of the disposal. The decommissioning and disposal aspects addressed will in most cases only consider a single reactor unit, but as features of LO1 and LO2 are mostly identical, same decommissioning and disposal methods can be applied to both units. The thesis will be written for Fortum Power and Heat Plc and will serve as background material for the official decommissioning plan provided for the authorities.

2 NUCLEAR DECOMMISSIONING

Decommissioning of NPPs is a complex multidisciplinary industry, which combines the features of highly specified radiological sciences with more rough methods of industrial decommissioning. While the traditional industrial decommissioning includes challenging activities (cutting and dismantling thick steel structures, lifting and hauling massive components, managing a complex organization and contractor structures, etc.), in nuclear decommissioning these activities must also follow the radiological specifications (radiation protection, decontamination, even more strict regulations and standards, nuclear safety regulations, radiological characterization of all waste, etc.). This complicates all the decommissioning activities, as rigorous attention to cleanliness must be paid due to radioactive contamination and many activities including planning and designing of works must be done remotely or simulated, as high radiation levels prevent working in close proximity of radioactive objects. (Laraia, 2018)

The International Atomic Energy Association (IAEA) defines two strategies for nuclear decommissioning, immediate dismantling and deferred dismantling, while the outcome of these operations would be that the facility poses no unacceptable risk to the environment, the population or the workers.

- In *immediate dismantling* strategy the facility is released from the regulations that determine usage of nuclear facilities as soon as possible after the permanent shutdown has been completed, by removing all radioactive material contained by the components, structures and equipment of the facility. This decommissioning strategy is preferred by IAEA.
- In *deferred dismantling* strategy the facility is placed in safe storage state after the permanent shutdown has been completed, in which nuclear fuel is removed from the facility and spread of radioactive material from the facility is eliminated. This strategy may offer some advantages in radiation doses accumulated during the decommissioning process, as some short-lived nuclides will decay during the storage period. However, this strategy should only be utilized if conditions strongly support it e.g., due to another reactor unit with shared systems still operating in the premises. (IAEA, 2014)

Third decommissioning strategy that is listed in multiple sources is entombment, which was based on encasing the facility so that no radionuclides leak out and that the encasing lasts until the activity has decayed to safe levels. However, according to IAEA Safety Standards this is no longer a valid planned decommissioning strategy and should only be used in case of a major accident. As entombment would simply postpone the responsibility of processing hazardous materials to the future generations and monitoring the site for several decades would pose unrequired risks. (IAEA, 2018)

The choice of decommissioning strategy and all activities done should be based on a careful and systematic evaluation of the following criteria:

- The national regulations and policies concerning nuclear power, radiation and waste management.
- Nuclear safety and security.
- The features of the facility, existence of other reactor units in the premises and possible shared systems between the units.
- The radiological and physical state of the facility.
- Desired outcome of decommissioning and reuse of the site.
- The existence of professional personnel who are familiar with the decommissioned facility and the availability of decommissioning methods and knowledge.
- The decommissioning consequences to the environment, society and economy.
- The radioactive waste management options and capabilities.
- The financial resources of the organization responsible for the decommissioning. (IAEA, 2018)

While modern NPPs are designed with consideration to the decommissioning aspects in mind, most of the NPPs currently operating are from a time when decommissioning was not regarded as an important design basis. Combining this with the fact that many of the facilities were not intended to be operated for multiple decades, many of the systems are not designed to be replaced or taken apart and many systems have received total overhauls making the system indefinitely complex. Consequently, planning the decommissioning of older facilities requires considerable amounts of effort, as the old original schematics might not be up to modern standards or in worst cases are nonexistent and the systems are often a combination of old and new technology with innovative solutions in between.

Today several (World Nuclear Association, 2021) older NPPs have already been shut down and many even decommissioned, so that some proven technologies and methods are already available. Proven meaning that the technology is actually used in NPP environment, as simply being widely used in other industries rarely means that the technology could directly be utilized in NPP. And while progress is being made, the challenges associated with nuclear decommissioning are still in multitudes, especially as every facility has their own unique features mainly depending on the type of the reactor, but also on the construction period and nation.

Depending on the national and international legislation approximately 68 % (Mostečak & Bedeković, 2018) of the waste generated when the NPP is decommissioned can be released to the traditional waste recycling and treatment facilities, the rest must be either temporarily stored to let the radioactivity decay to a level where the waste can be cleared, or a final disposal solution must be provisioned. While several of the NPPs around the globe have already been decommissioned, none of the countries operating nuclear power have a final disposal site for used nuclear fuel and many of these countries do not have a final disposal site for low- and intermediate-level waste (LILW) either. And even if a final disposal site is operational, they are often located in an isolated location far away from the facility being decommissioned, which in turn requires risky and costly haulage of the waste across public traffic routes. While large amounts of LILW are often disposed of to burial sites, waste with higher level of activity are rather stored in an interim storage facility to wait for a final solution to be decided. This naturally means that the waste stored in the interim storage facilities needs to be packed and handled so that it is possible to be taken out of the storage facility and reprocessed on a later occasion. Loviisa NPP however has a final disposal site ready and operating on the premises of the facility, which eliminates the need to haul the wastes for long distances and the wastes can also be sited without consideration to the possible future reprocessing.

As stated before, the decommissioning process of the RPV and RPVI is the single most challenging task of the NPP decommissioning. In Loviisa these components contain more than 95 % of the total activity of the facility combined (Jansson et. al., 2019), not including nuclear fuel, and the RPV is the heaviest (200 t) individual component that has to be moved during the decommissioning. In the majority of decommissioned NPPs these parts have been dismantled to smaller parts before packing and disposing them to interim storage facility. At present this approach is often also the one and only considered when the decommissioning is being planned. However, there are a couple of previous occasions where the RPV has been taken out of the reactor building without segmentation.

Largest one of these was the 1 130 MWe pressurized water reactor of Trojan NPP, located in the United States near the Columbia River northwestern part of state Oregon. The facility was permanently shut down after only 17 years of operation in 1993. The decommissioning work begun in 1996 and the RPV was placed in a burial trench in 1999. The RPV and RPVI of the Trojan NPP were lifted out from the containment building as one package (940 t) with radiation shields installed in place. A mobile jacking system and robust gantry were utilized to lift and haul the package out. The assembly was then hauled with heavy transport platform to a barge in Columbia river, where it was barged to its final disposal site over 400 km away. (EPRI, 2000)

Second example of a nuclear reactor to be removed from the reactor building without segmentation is a pebble bed prototype reactor formerly located in Jülich Germany. The final shutdown of the reactor was carried out in 1988 after 20 years of testing the prototype, while the decommissioning work begun in 2012 and the RPV was transported to an interim storage facility in 2015. Even though the radioactivity of the reactor components had over 20 years to cool down, the whole facility was covered with temporary containment building before moving the RPV. In Jülich facility the packed RPV weighted 2 000 tons and it was lifted out using strand jacks and a robust gantry system, while the 600-meter hauling to the interim storage facility was done by a self-propelled modular transport (SPMT) platform. (World Nuclear News, 2015)

In case of Loviisa NPP, the chosen strategy for decommissioning is immediate dismantling. This strategy has been chosen based on different reasons. Most importantly the Finnish Nuclear Energy Act imposes that facility decommissioning may not be delayed without due cause (Act 11.12.1987/990). Fortum also wills to utilize the existing personnel already working in the facility, as they will have most up to date knowledge of the condition of the facility and know-how on operating the systems. Additionally, it has been estimated that the expenses required to be invested on the facility upkeep, property taxes and other expenses would exceed the savings acquired from deferred dismantling (Kaisanlahti, 2018). The designed outcome of nuclear decommissioning activities in Loviisa is a brownfield, which means that the Hästholmen island is not restored to its natural state, but rather left to a state for later industrial development.

2.1 Radioactivity

This chapter will go through the fundamentals of radioactivity and how radioactive materials are formed in the NPPs, as radioactivity is one of the major design basis concerning all the work phases in NPP decommissioning. The processes of radioactive decay and neutron nuclei interaction are very complicated and involve many quantum mechanical effects, so consequently they are not addressed here by going through every detail. But rather a simplified and short explanation is given to underlay the issues discussed later.

Science has identified over 3 200 different nuclides so far, but only less than 10 % of these nuclides are stable and over 2 2880 of them are so unstable that they have a half-life below one hour. The unstable nuclides have an unfavorable composition of neutrons and protons, so that their binding energy is not sufficient enough to keep them together. These unstable nuclides i.e., radionuclides will in turn convert to stable ones with a more favorable ratio of neutrons and protons in the nucleus. This transformation process is known as radioactive decay and it happens spontaneously as an exothermic process releasing decay energy. In most cases unstable nuclides require multiple transformations to occur, before reaching the final stable state of the decay chain. The spontaneous decay of a nuclide is not affected by physical or chemical external effects, such as pressure, temperature or pH of a medium. Even though it would be useful to trigger the decay event when required, as this would eliminate the need of storing the unusable radioactive material for extended time periods. In fact, quantum mechanics define that predicting a single decay event is impossible. However, as the number of atoms in any real-life application is so immense, a statistical decay constant can be used to express the probability of a decay event occurrence, from which a half-life of any given radioactive material can be derived. Half-life quite frankly defines the time required for the original activity to be halved. The half-lives of different radionuclides range from barely measurable 10^{-24} seconds, to incomprehensible eons of 10^{24} years (IAEA, 2021). (Rösch, 2014)

The important part concerning the presence of radionuclides in the decommissioning process of a NPP is that the transformation process is exothermic, and the majority of the released energy is emitted as gamma photons or as kinetic energy of particles in the form of alpha or beta radiation. These are the three main types of ionizing radiation or more commonly known as radioactivity. The ionizing radiation can pose a major health hazard to the workers decommissioning the facility, or to a local biota of the area in case the nuclides are released from the waste repository in the future. The type and amount of the energy released depends on the decay type of a nuclide and so the activity of a nuclide is not directly proportional to the health hazard it poses, e.g., Co-60 representing 21 % of the RPV activity can cause much higher doses to the workers than Fe-55 representing 64 % of the RPV activity, as the decay event of a Co-60 can release almost 20 times more energy than the decay event of Fe-55.

In NPP decommissioning radionuclides can be roughly divided into two groups: short-lived and long-lived ones. The nuclides with shorter half-lives mostly affect the safety of decommissioning work done, while the long-lived ones mostly affect the long-term safety of the waste disposed of. The nuclides that pose the most challenges in the decommissioning work include strong gamma emitters, such as Co-60 ($T_{½}$ = 5.27 a), Cs-137 ($T_{½}$ = 30.06 a) and Eu-152 ($T_{½}$ = 13.53 a) (IAEA, 2021). Nuclides that have comparably short half-lives, e.g., around 5 years and below will not have a major effect to the long-term safety and most of them have already decayed to remarkably safer levels before the waste repository is even closed. The long-lived nuclides affecting the long-term safety in turn include nuclides such as C-14 ($T_{½}$ = 5 700 a), Cl-36 ($T_{½}$ = 300 000 a) and Ni-59 ($T_{½}$ = 76 000 a) (IAEA, 2021).

The activity emitted at any given moment is inversely proportional to the half-life of the nuclide in question. Therefore, in most cases the accumulated dose from the long-lived nuclides is not so high as from the short-lived ones and they have only a limited effect on the doses during the decommissioning work. Rather the long-lived nuclides can have negative health effects, if the radioactivity is later accumulated on present biota during a longer time period. These nuclides presented are only a small example of the actual activity inventories, that include several hundred different nuclides which all have different half-lives, decay events and decay chains all with different effects to the surrounding environment.

When the NPP is operating, a large number of short-lived nuclides ($T_{½}$ < 3 a) are present and consequently some of the radiation measurements done while the facility is operating cannot be applied to decommissioning work, as the radiation emitted by these short-lived nuclides cannot be easily distinguished from the longer-lived nuclides.

2.1.1 Neutron interactions and material activation

In case of nuclear power plants, radionuclides are produced due to high neutron irradiation from fission reactions taking place in the reactor core. The neutron interactions with atomic nucleus can be divided to scatterings and absorptions, where scattering means that the neutron keeps travelling with exchanged speed and direction, while absorption means that the neutron is captured by the nucleus. Besides causing fission reactions which maintain the chain reaction required for the reactor to operate, neutrons captured by non-fissile nucleons will cause them to reach an exited state i.e., turn to unstable nuclides. This will naturally happen to the RPVI and coolant materials in the core region and occasionally neutrons escape the reactor activating the RPV and other nearby materials. When considering the abundance of neutrons present, these occasional escapes result in high amounts of material being activated.

Probability of neutron interactions depend mainly on two factors; the cross section, which is the probability of neutron interacting with matter it passes through, and the neutron flux, which is the number of neutrons crossing a unit surface area. The cross section can be conceived as the size of the nucleus from the viewpoint of the incoming neutron, the larger the cross section the more likely it is for the neutron to interact with the target. Even though the cross section can be viewed as area and value for it is given in units of area, it is not technically speaking a physical measurement, but rather a quantum mechanical probability and it does not intuitively increase when the number of subatomic particles in nucleus increase. The conditions affecting the neutron interaction probability are mainly the neutron speed and temperature of the environment, which affects the cross section of the target element by Doppler Effect. (Reuss, 2008)

Values for the cross section are often represented with macroscopic cross section, which is inverse of mean free path of the neutrons. Simplified view of this would be that it represents the probability of interaction between nucleus and neutrons. Macroscopic cross section can be written as follows:

$$\Sigma = N \cdot \sigma \tag{1}$$

where N [#] is the number of nuclei per unit volume in the material that the neutrons are traveling through and σ [barn, 10^{-24} cm^2] is the microscopic cross section of target isotope being observed. The microscopic cross section on the other hand is totally dependent on the isotope in question, and the value must be acquired from databases based on physical reaction tests made on the given isotopes. Each possible interaction (scattering, capture or fission) is given their own value and in case of activation event the capture cross section (σ_c) is used. The value of a microscopic cross section varies greatly depending on the speed of the neutron, so these calculations must be done separately for neutrons traveling at different speeds i.e., having different energies. (Reuss, 2008)

The number of nuclei per unit volume can be calculated from the composition and mass of the material:

$$N = \frac{\alpha \cdot \beta \cdot m \cdot N_A}{M} \tag{2}$$

where α is the mass fraction of the target element [%], β is the proportion of the target isotope in material [%], m is the mass of the component [g], N_A is the Avogadro constant [1/mol] and M is the atom weight of the target isotope [g/mol].

The neutron flux is quite simply the number of neutrons passing through a volume. Although, the word flux in this case is not an accurate term as it would indicate a number of neutrons passing through a surface area, while having a direction as in other fluxes e.g., heat or energy fluxes. While in neutronics the flux it is rather concept of density, without having vectoral quantities like other fluxes. But nonetheless, this term that has been established in neutron physics and the industry can be defined as:

$$\phi = n \cdot v \tag{3}$$

where n [1/cm^3] is the average number of neutrons found in volume and v [m/s] is the neutron speed or rather energy, as electron volts are mainly used. The average number of neutrons is directly proportional to the power level of the reactor i.e., how many new neutrons are born due to fissions. The energy of the neutrons from fission reactions are around 2 MeV and in thermal nuclear reactors they are gradually slowed down to an energy of 0.05 eV. (Reuss 2008)

The rate of activation events can be calculated by combining equations (1) and (3) to form a reaction equation for capture interactions:

$$R_c = \Sigma_c \cdot \phi \quad (4)$$

Where the Σ_c [1/cm] is the material dependent macroscopic cross-section and ϕ [neutrons/cm^2/s] is the neutron flux from the reactor core. When integrating this equation over operational cycles of the reactor, a total number of activation events i.e., the amount of activated material can be acquired.

2.1.2 Contamination

The majority of the decommissioned material from NPPs is not directly activated, as the neutron irradiation only affects imminent surroundings of the core region and is diminished by the heavy shielding offered by the water coolant, reactor structures and the concrete biological shield. However, the activity originating from the core region often spreads as small particles of activated materials near the core are detached, or if the coolant contains impurities that get activated in the reactor core. These particles are then transported by the flowing coolant which will spread them around the primary circuit, where the particles may stick to nonactivated components. As the contamination is located only on the surfaces of components, they can be decontaminated by washing them with acidic solution or mechanical grinding. This is not always a viable option as the component structure is often complex and the contamination can stick to the surface firmly and the decontamination process itself might produce more problematic waste, as the contamination will just be transferred to another medium.

2.2 Radiation protection

The excessive levels of ionizing radiation present during the NPP decommissioning is harmful or even fatal to humans and as such it must be carefully considered in every stage of work done. Easiest way to keep the radiation dose in minimum is to keep sufficient distance to the active components. In most cases the hazard from alpha and beta radiation can be avoided by good contamination control, as their penetration energy is not high enough to cause harm from any significant distance and they mostly cause harm only if they get ingested. The gamma rays however, are in totally different category, as they can easily penetrate objects and travel much farther away in air. When working with the RPV components simply keeping a sufficient distance is not a viable option, as the radiation might be so intensive that the distance required would mean that no work can be performed.

In addition to the biological damage the ionizing radiation can cause damage to sensitive electronic components. This can either happen by lattice displacement, where the radiation alters the lattice structure of the semiconductive components, physically damaging the components and ultimately leading to component failure. Or by ionization effect, where the energy of charged particle generates electrical current on the circuitry possibly altering digital signal or causing a short circuit. Where the short circuit could cause physical damage to the circuitry and the signal change could cause the functioning of the device to temporarily change e.g., crane could get a signal to drop its load by a such charge. (Velazco et. al., 2019)

To follow the base principle of radiation protection “as low as reasonably possible” (ALARA) in avoiding radiation doses, work done with the RPV components should be performed by remote controlled methods or sufficient radiation shielding should be provided. When considering the radiation shielding, a simple estimation is that denser the material the better it is at blocking the radiation, e.g., lead is often used when the size of the shielding material is somehow limited. And as the dose accumulated is dependent on the exposure time, the decommissioning work should be completed as quickly as safe performance allows. Here careful and precise planning of work tasks is vitally important, as mistakes made while carrying out the activity along with unpredicted conditions lead to prolonged completion of work tasks, which results in higher exposure times of workers.

2.3 Decay heat

The decaying radionuclides generate heat, as their decay energy is absorbed to the surrounding materials. Although the heat generated by the radionuclides in the decommissioned reactor is not substantial compared to the operating reactor or the decay heat from spent nuclear fuel, it may still cause damage to the decommissioning waste packages or affect the working conditions of the waste repository and thus it must be accounted for.

The main heat-generating radionuclides on the RPV and the RPVI are Co-60, Fe-55, Ni-63 and Mn-54, in which Co-60 represents nearly 97 % of heat generated, all these radionuclides have relatively short half-lives and consequently only have relatively short-term effect. When considering the effects of decay heat to the decommissioning work presented in this thesis only these four nuclides are considered. The heat generation of a nuclide can be calculated from

$$\frac{dQ}{dt} = A \cdot E_{decay} \qquad (5)$$

where dQ [W] is the heat generation, A [Bq] is the activity and E_{decay} [J or keV] is the energy released from decay event and absorbed in the structure. In this thesis the heat generation in watts is calculated using Grove Software's Microshield – Heat Energy Generation Tool 12.02. To make conservative estimates of the heat generation, all the decay energy, excluding neutrinos, can be assumed to be absorbed to nearby surrounding materials.

2.4 Figures of merit for decommissioning

The figures of merit of different decommissioning options presented in this thesis are the time taken to complete the required decommissioning work stages, collective radiation dose accumulated during the decommissioning process, the cost difference between the options and the dose release rates during the long-term assessment period. The options will also be assessed based on their impact on the decommissioning process on the facility level, this however will be done very generically as the details of many decommissioning aspects have not yet been agreed on.

3 ACTIVITY INVENTORY AND RADIATION FIELD SIMULATION

Activity inventories are used in nuclear decommissioning as source information for the activated materials to be decommissioned. They list the different isotopes contained by the materials so that the different dose rates from processing the materials can be estimated. Activation calculations from which the inventory is formed can be done with deterministic methods, by utilizing neutron transport and activation equations. However, in the case of an operating nuclear reactor, solving these equations comes increasingly difficult, as the equations are coupled with changing conditions such as reactivity feedbacks and fuel burnup. Deterministic methods are also best suited for solving two dimensional problems and as the reactor operates in three-dimensional space, it is better to employ probabilistic methods such as Monte Carlo N-Particle (MCNP) transport code.

An early version of Monte Carlo method was first experimented by Enrico Fermi in 1930s as part of a neutron diffusion studies and the modern version of Markov Chain Monte Carlo method was subsequently developed by Stanislaw Ulam, while he was working for Los Alamos National Laboratory (LANL) in the nuclear weapons program in 1940 (Metropolis, 1987). The Monte Carlo method is based on statistical probabilities, where the results are obtained by simulating a large number of single neutron paths and recording their histories i.e., the path that the neutron will take from its origin to an absorption event. So rather than discretely solving how the neutrons interact with materials, each interaction is given a probability of happening and as a result a probability of neutron ending its path to an activation event is acquired after multiple neutron paths are recorded. The same method can be utilized when dose rates from gamma radiation are calculated, but instead of neutrons gamma photon paths are recorded. (Leppänen, 2021)

The MCNP-code solves the activity from statistical estimation of the transport equation in following integral form:

$$A = \left(1 - e^{-\lambda t_1}\right) \cdot e^{-\lambda t_2} \cdot \frac{\alpha \beta m N_A}{M} \int_{E_{cutoff}}^{\infty} \sigma(E) \cdot \phi(E) dE \tag{6}$$

where λ is the decay constant [1/a], t_1 is the irradiation time [a], t_2 is the decay time [a], and E_{cutoff} is the cutoff energy used for Loviisa activation calculation [$2 \cdot 10^{-10}$ MeV]. (Kupiainen et. al., 2019)

3.1 MCNP6

MCNP6.2 is a general-purpose, continuous-energy, time-dependent, generalized-geometry Monte Carlo N-particle transport code developed and maintained by LANL. The code is able to track different particle types like neutrons, photons, protons, alpha particles and other elementary particles over a wide range of energies. This versatility offers a possibility to perform both calculations required in decommissioning work with same code, the material activation calculations as well as gamma radiation shielding calculations. (Werner, 2017)

MCNP6.2 is distributed by Oak Ridge National Laboratory (ORNL) and it is categorized as an export-controlled software by Radiation Safety Information Computational Center, consequently it is not directly available to public distribution. ORNL however offers a wide variety of different software packages to be used by research organizations and companies, after required safety checks have been completed.

3.2 Problem solving process

The MCNP6.2 on its own is only the solver to calculate the wanted neutron or photon histories required for presenting the statistical results of a given problem and it doesn't offer a graphical user interface, rather the input and output of the software is handled with plain text files. The input files are used to configure the problem presented and must be typed manually following the format accepted by the software. The MCNP6.2 handles the input data as form of cards, which are presented as different rows of the input text file. These cards are divided in geometric shape defining cell and surface cards, data cards which define other calculation parameters, such as materials, source terms, termination conditions, accuracy of calculation mesh, etc. In addition, the manual introduces a wide variety of options to improve the problem-solving speed, accuracy and other calculation terms.

While the actual input is handled manually, there are some external tools to ease the process of making the input files. MCNP Visual Editor is one of these and it's used to visualize and create geometries of the input file. However, the creation of the geometries is often complex and small mistakes made with the editor may break the input file. Thus, it is preferable to create the geometries by text editor and use the Visual Editor only to check the correct positioning of components and sources.

Output of the MCNP6.2 is also acquired in text format and in case of activation or radiation dose calculations, a mesh format of the information is usually used. Pure text format of the results is however hard to analyze as such and again some visualization software should be utilized. For radiation dose calculations the MCNP6.2 only solves the amount of gamma photons present in the result cell, to convert this to a dose rate (Sv/h) Fortum has written a program called MCNP Mesh Visualizer. With Mesh Visualizer photons of different source isotopes can be summed together and visualized with color contours.

3.3 Activity inventory

When making the activation calculations with MCNP, creating a geometrically and physically accurate model of the reactor is not the only challenge that needs to be solved. The activation of the materials strongly depends on the neutron flux directed at them, which in turn depends on the power level of the reactor, so different loading patterns and other changes in operating parameters of the reactor such as amount of boric acid should be taken into account. When the geometry is created activation of materials can be solved by running the MCNP solver with different source terms and material configurations for each operating cycle of the reactor and summing up the activity results acquired. The most notable change in every operating cycle is the loading pattern of the fuel elements, which affects the neutron flux everywhere near the core region. In addition, the loading pattern of the shield elements affects the number of neutrons leaking out of the reactor. This will in turn affect the distribution of activity between the shield elements and the reactor components.

The activity inventory used in this work is based on an existing activity inventory (Kupiainen et. al., 2019), which is a modified version of the original MCNP-calculations (Eurajoki & Ek, 2008). For the purposes of this report the activity values of the reactor components have been picked from this activity inventory and some of the results have been summed up, as the components cannot be segmented the way the MCNP-model has been structured. The activity values summed from the original activity inventory are the values given for; the activity distributed in different depth levels of the thick steel plates (PTU plate and basket bottom) and the different components forming the shell of the core basket (baffle and basket).

The original activity values are calculated on the facility shutdown date, so two years decay time for the radioactivity has been assumed to keep radiation effect estimations conservative, when the transition phase after facility shutdown is estimated to be three years (Kaisanlahti et. al., 2018). The radioactive decay of the isotopes follows universal exponential law and can be solved with the following decay equation:

$$N = N_0 \cdot e^{-\lambda t} \tag{7}$$

where the *N* is the number of particles and N_0 is the initial number of particles (Reuss, 2008). As the activity is directly proportional to the number of radioactive particles present, the *N* here can be replaced with *A* to directly solve the activity of any given substance. The summed-up activities of the components are presented in Table 1 and the nuclide specific activity inventory can be found in Appendix 1.

Table 1. Total activities of the components and the relative percentage of the total activity (Kupiainen et. al., 2019).

Component	Total activity 2032 [Bq]	Percentage of total activity [%]
RPV Cladding	2.05E+14	0.20 %
¼ RPV	2.74E+14	0.30 %
¾ RPV	7.73E+13	0.10 %
Barrel	7.11E+15	7.50 %
Barrel bottom	2.89E+13	0.00 %
Core basket	2.25E+16	23.6 %
Core basket bottom	2.31E+15	2.40 %
PTU	9.62E+14	1.00 %
Shield elements	6.15E+16	64.5 %
Control rods	1.14E+14	0.10 %
Metal scrap[1]	2.70E+14	0.30 %
Total	**9.52E+16**	**100.0 %**

[1] Metal scrap container was added to the inventory in 2018 safety case, it contains metal scrap from spent fuel assemblies as well as some activated metals from the dry silos. Only one container exists, rather than one per reactor unit. (Kupiainen et. al., 2019)

4 COMPONENTS TO BE DECOMMISSIONED

This chapter will go through the structure and purpose of the components to be decommissioned, the idea is to give the reader an understanding of the structure of the reactor unit and a rough description to the dimensions and thicknesses of the components handled. End of the chapter will also describe the source materials and methods used in making the CAD-models, as well as results obtained from the modelling process.

4.1 Reactor pressure vessel

Figure 1 displays the Loviisa RPV and the RPVI, this is a VVER-440 type pressurized water reactor with distinctive VVER-type hot- and cold-side nozzles on different levels. In total there are 17 penetrations in the RPV itself, 12 nozzles with diameter of 500 mm for the main circulation loop, four nozzles with diameter of 245 mm for high pressure emergency core cooling system and one 260 mm penetration for instrumentation. In addition, the vessel head has 37 penetrations for the control rods and 18 for the core instrumentation. The RPV height is 11.8 m and with the vessel head on it is increased to 13.8 m, outer diameter of the vessel is 3.8 m, and on the flange where it is widest the diameter is 4.3 m. The RPV weights 200 tons and with all internal components and the vessel head the total mass is 439 tons. The RPV is mainly made out of 140 mm thick heat resisting Cr-Mo-V steel (15X2MØA) with 9 mm welded austenitic steel coating on the inner wall (Kohopää, 2011).

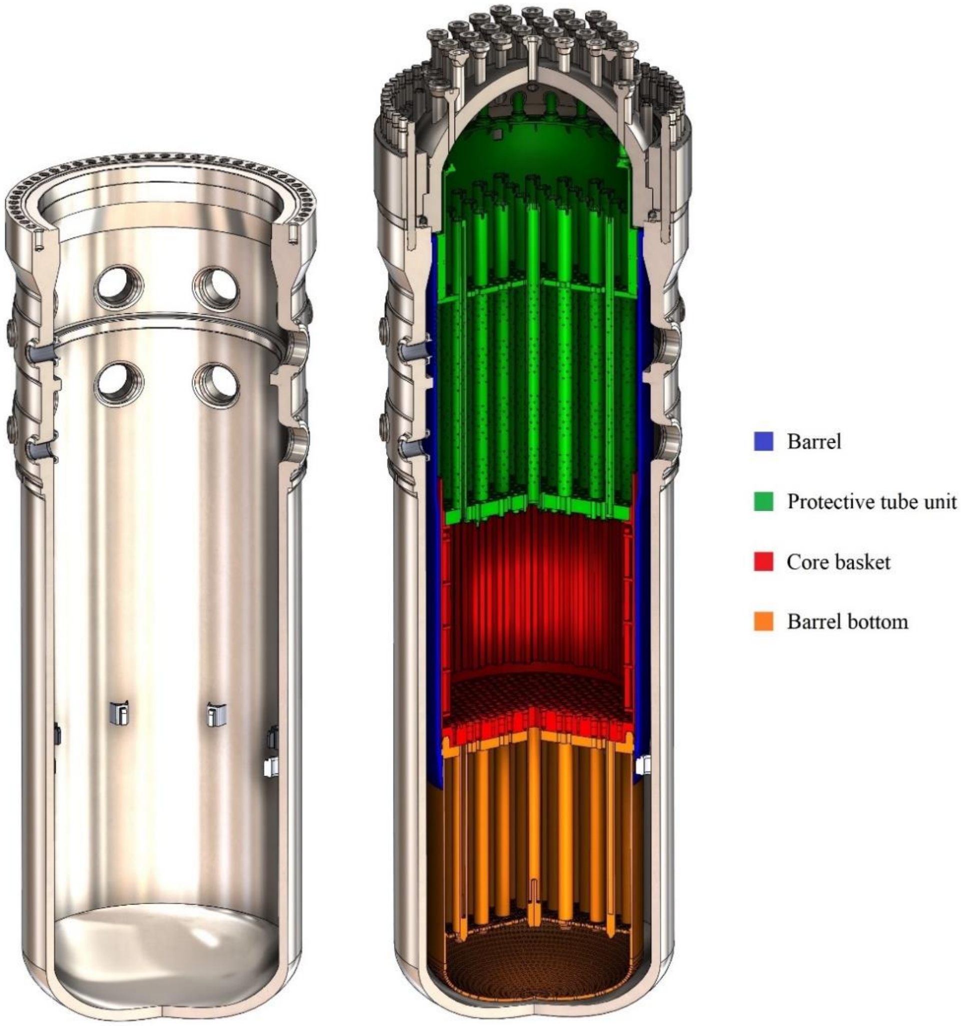

Figure 1. The RPV and the RPVI; protective tube unit (green), core basket (red), core barrel (blue) and barrel bottom (orange).

4.2 Reactor internals

VVER-440 reactor design consists of four internal parts that can be removed from the reactor during the maintenance and refueling outages (Figure 1). These parts are not fastened to each other nor to the RPV, they rather slide into their places and are held in position by the pressure from the vessel head. This design decreases the risk of parts getting jammed due to mechanical malfunctions or thermal distortions and allows easy dismantling of the RPVI by simply lifting the parts up from the RPV. The internal components are mainly made of low cobalt content (< 0.035) austenitic steel (08X18H10T) (Korhonen, 2011).

4.2.1 Barrel

The main function of a barrel unit is to seal the flow of the coolant between hot and cold sides of the reactor (Appendix 2). In addition, it carries the weight of the other internal parts and has retainers that prevent the other components from turning horizontally, it also houses material sample chains used in neutron irradiation embrittlement studies. The thickness of the barrel wall is 60 mm on average and the upper part has holes that allow the coolant to flow out from the hot inner side of the reactor.

4.2.2 Protective tube unit

The protective tube unit (PTU) keeps the control rods and core instrumentations on their specific positions while allowing the coolant to flow through (Appendix 2). It also holds 72 spring units that transfer the pressure from the vessel head to the lower parts of the reactor, preventing any upwards movement of components inside the RPV. The PTU consist of a 200 mm thick top core plate that holds the top ends of the fuel and shield elements in place, a 30 mm thick shroud covering the top part, and 37 control rods tubes with wall thickness of 8 mm. There is also a large amount of smaller 6 – 10 mm tubes protecting the instrumentation cables, these small tubes are however not displayed in the CAD-models.

4.2.3 Core basket

The core basket is the main component keeping the fuel and shield elements in their places, in a VVER-440 unit it may hold up to 349 of such elements. The bottom of the core basket consists of a 290 mm thick bottom core plate carrying the weight of the fuel and shield elements. In addition to the holes for the elements, the plate has 37 hexagonal openings to allow the control rod extensions to pass through. The shell of the core basket is 30 mm thick and in addition a hexagonally shaped 8 mm thick baffle plate is connected to the shell. This baffle supports the fuel and shield elements horizontally.

4.2.4 Barrel bottom

The barrel bottom carries the weight of the core basket and PTU, it also directs the coolant flow from the bottom of the RPV to the core (Appendix 2). The barrel bottom consists of a 150 mm thick top plate, 37 tubes with a wall thickness of 30 mm, and a shell that has a wall thickness of 50 mm.

4.2.5 Shield elements

The VVER-reactors do not have shield elements by default, but for the reactor of Loviisa NPP they were added as some unexpected embrittlement of RPV materials caused by neutron irradiation was observed. One shield element consists of a fuel element sized structure that is filled with steel to block the neutron irradiation from reaching the RPV without blocking the flow of the coolant. Two different designs of the shield elements exist, an older one that consist of interlaid tubes and a modern one that has seven solid steel rods inside it. Currently both reactor units have 36 of such elements in place and there are a total of 290 (Lehtinen, 2021) elements expected to be disposed of, when the facility is to be decommissioned.

4.2.6 Control rods

Control rods follow the hexagonal design of the fuel elements but are somewhat shorter and contain borated steel, that efficiently absorb neutrons and thus reduces the fission chain reaction. 37 rods are used in the reactor core and a total of 376 (Mayer, 2008) pieces are estimated to be disposed of, when the facility is to be decommissioned.

4.3 CAD-models

The CAD-models of the RPV components were made with Dassault Systèmes Solidworks 2019 and are mostly based on the original Soviet technical drawings of the VVER-440 reactor. The aim of the model was to serve the decommissioning purposes and therefore, some of the smaller details of the components have been left out or they have been roughly simplified. Details of the components left out or simplified were done roughly based on the availability of the technical schematics of the reactor. If a component did not have dimensions on the main assembly schematics, it was left out or the dimensions were estimated based on the surrounding measures or the scale of the drawing. The scale of the digital drawings might have been distorted many times during the history, when they have been copied and scanned to digital form. The manufacturing methods used in the 1980s might have also caused some minor differences between the drawings and the actual products.

The overall difference to the actual dimensions is probably within millimeters, but there are details where no close numerical dimension could be found and as such these could have higher deviation from the actual dimensions. Consequently, dimensions should always be checked on site before any actions or specific tools are made. The accuracy of the current models should however be sufficient to form the design basis for decommissioning methods. Here the focus of the modelling was to get the main dimensions right, so that handling methods for the components could be determined with good accuracy and a proper segmentation plan could be made.

The major CAD-assembly (Figure 1) is divided to six subassemblies, vessel head, barrel, PTU, core basket, barrel bottom, and RPV. These subassemblies combine the different parts of the reactor based on the component configuration on how the reactor can be disassembled during the yearly maintenance outages. Most of the parts forming the subassemblies are also welded together, so the only way to disassemble them is by cutting.

When the CAD-models are configured with the correct materials they also provide values for surface area, mass, and volume of the components. These values are presented in Table 2 and are used to estimate different aspects of decommissioning and the later discussed long-term safety case.

Table 2. The RPV and RPVI measurements.

Part	Mass [t]	Surface area [m^2]	Volume [m^3]	Free internal volume [m^3]
RPV	200.05	312.99	25.65	112.20
Vessel head	80.42	252.67	10.63	9.64
Barrel	35.27	189.68	4.52	-
PTU	30.51	338.88	3.91	-
Core basket	20.79	200.09	2.67	-
Barrel bottom	27.77	255.85	3.56	-
Shield element[2]	0.25 / 0.31	7.58 / 5.85	0.03 / 0.04	-
Total	**439**	**2398**	**57**	**122**

[2] 93 old / 56 new shield elements are included in total values (Jansson et. al., 2019).

5 DECOMMISSIONING

Different alternatives have been evaluated for the decommissioning of the RPVs of Loviisa NPP. The focus of these alternatives has been on segmentation of the components versus the possibility of disposing the reactor components without segmentation. In this chapter three of the alternatives are addressed with more detail, these alternatives are:

- *No segmentation of components*. In this option the RPV and the RPVI are decommissioned as whole and disposed of in a silo excavated to the waste repository.
- *Segmentation of all components.* In this option the RPV and the RPVI are segmented and packed inside steel containers, which are then disposed of to decommission waste hall 1 (DWH1).
- *Segmentation of reactor internals.* In this option the RPV is decommissioned as whole and the RPVI are segmented and packed inside steel containers, all of these are then disposed of to the DWH1.

Other options evaluated in an earlier report (Kälviäinen & Kaisanlahti, 2018) included two more options, segmenting the internal components into a large pieces while the RPV would be either segmented or disposed of as whole. These were however deemed hard to implement, as the packages of the large internal components with necessary radiation shielding would be massive and they would take up much larger space of the waste repository.

Packing the internal components into the RPV, while the RPV is in a horizontal position in the waste repository, has also been considered, but so far no thorough evaluation has been done. While this would eliminate the need of excavating the silos, horizontal packing would pose new challenges for the placement of the components. As they were designed to slide into the RPV from top to bottom and horizontally they would need to be pushed inside. This would require a total overhaul of the component handling equipment, concrete filling technique of the vessel, and rethinking of the radiation protection required. So, this option is not considered in this thesis, but it should be kept in mind, if for example, fracture zones in the bedrock prevent excavation of the RPV silos.

The CAD-models of the reactor hall structures and some of the facility components utilized here were originally made by E. Mayer and the original Bentley MicroStation models have only been cleaned and imported to Solidworks format for this thesis.

5.1 Initial and shared conditions

Before the RPV decommissioning can begin and regardless of the alternative chosen, some activities are assumed to be performed. All activities in the three-year preparatory phase are assumed to be completed, most importantly the removal of nuclear fuel from reactor building; drainage, dismantling and possible decontamination of the primary circuit, placing the internal components into wells one and two, making a hauling opening with a temporary door to the containment building on the level +10.45 assembly area, and building a lifting gantry for large components down from the assembly area to the yard level +2.85. Although, when the RPV and internal components are segmented, this hauling opening and lifting gantry are not necessarily required for them. But as they are required for other large components of the facility, they are assumed to be built regardless of the decommissioning option. (Kaisanlahti et. al., 2018)

The decommissioning options also share multiple features, so some of the required work stages and methods can be assumed to be almost identical. These work stages or methods are presented here instead of going through them for each decommissioning option.

5.1.1 Waste characterization

When decommissioning possibly radioactive components, the activity of the materials must be determined, to form a basis for correct dismantling strategy and long-term safety estimation. As the components of the RPV and the RPVI are large and highly activated, direct activity measurements with dose rate meters or gamma spectroscopy cannot be utilized. Instead, an activity inventory made with MCNP modelling is used. Even though the modern MCNP modelling can be very accurate and reliable, some assumptions must be made when the models are created. So, before the actual decommissioning work with the RPV can begin, the activity inventory from MCNP model must be validated by taking material samples from different locations and measuring their activity in a laboratory. Based on current plans three samples from the RPV would be sufficient to validate the results. However, when the complexity of the model and reactor structure are considered, many more samples are probably required to ensure that the components can be divided in correct homogenously activated groups. (Seitomaa, 2020)

5.1.2 Logistical solutions

Hauling

The transportation of disposed of elements to the waste repository will be done with one or two SPMTs. When combined the SPMTs are capable of hauling weights up to thousands of tons and single eight axle trailer can transport 480 tons. If more weight needs to be transported or if the weight needs to be distributed to a larger area, additional trailers can be added to work as a single unit. The height of an eight-axle trailer is between 1.2 – 1.8 m, width of a single unit is 2.43 m and length with power pack unit is 14 m. When two units are combined the width grows to 5.33 m. The weight of a single unit is 34 tons, and the power pack unit weights an additional 4.5 tons. Other useful features of the SPMT include hydraulic height adjustment (0.6 m), load sharing on multiple wheels, ability to move in any direction and turn on its place. The SPMT are also remotely operated, which allows the operator to keep distance to the radioactive load. (TII Group, 2021)

Lifting

Most of the lifting operations done in the RPV decommissioning is performed with the 265 ton (Ögård, 2020) polar crane in the containment building, which can be operated from a shielded compartment minimizing the radiation doses to the crane operators. When the RPVI are lifted, an additional radiation shielding cylinder (RSC) is used. This cylinder already exists and is used during the maintenance outages of the reactor units. The shield elements and control rods also require a specific radiation shielding when lifted out of the water, which already exists also and is used when the said elements are handled. When the RPV is lifted, a lifting tool is required to reliably attach the heavy vessel to the polar crane. By making this lifting tool from 180 mm thick steel plate, it will also work as a radiation shield.

The lifting operations in the waste repository are performed either with fixed cranes of the waste repository or with temporary hydraulic jacks. The overall performance considering the whole facility decommissioning needs of the waste repository should be considered here, as installing fixed cranes that are capable of lifting the RPV components or packages and then sealing them to the waste repository could be uneconomical. When simply unloading the packages or components to the DWH1, the hydraulic lifting capacity of the SPMT can be utilized.

5.1.3 Detaching the RPV

In all decommissioning options the RPV needs to be disconnected from the primary circulation loop, the emergency core cooling system and the instrumentation. And before lifting the RPV, the bellow sealing the reactor pit bottom needs to be cut and the RPV support structures need to be disassembled.

To minimize the radiation doses, the RPV is filled with water up to the level of the lower main circulation nozzles (+10.85) and the 180 mm thick lifting tool is installed on top of the RPV. Installation of the lifting tool is made with eight 120 mm bolts, that are tightened to the existing holes of the vessel head bolts. At this point the polar crane should be connected and tensioned lightly to make sure the RPV will not drop during the cutting process.

The disconnecting process will begin with the removal of the thermal insulation plates around the RPV nozzles and the lower biological radiation shielding on level +10.85, the shielding should however be removed only where it obstructs the work. The nozzles can then be cut with an inside-out milling machine or a plasma cutting machine. The milling machine is the preferred working method as it will not cause radioactive aerosols and the cut will be cleaner allowing easier installation of further parts. In total there are 12 pieces of DN500 nozzles and 5 pieces of DN 250 nozzles. (Mayer, 2008)

After all the couplings have been cut, wedges (8 groups) of the RPV support ring on level +10.85 are removed and the bellow sealing the reactor pit on level +14.65 is cut open (Mayer, 2008). Again, this can be done with plasma, but mechanical cutting methods would be preferred due to contamination risk.

5.2 No segmentation of components

In this decommissioning option the RPV and all the RPVI are disposed of without segmentation, the RPV will also function as a release barrier and no additional waste packages are required. This decommissioning option has been the default option for Loviisa RPV, and the main work stages are designed by E. Mayer, in this thesis the details have been reconsidered and partly updated with modern solutions.

5.2.1 Packaging

To make the RPV function as a release barrier for long-term safety it must be hermetically sealed. This requires that all the openings including the top of the RPV will be sealed.

Closing the nozzles and instrumentation penetrations can be done after the RPV has been disconnected from the main circulation loop, but before the support ring wedges have been removed. The closure is done by welding 20 mm thick stainless steel plates inside the penetrations, so that the welding seam will merge the stainless steel plate and the stainless steel cladding hermetically, as seen in Figure 2. Welding the plates to the carbon steel of the outer shell of the RPV would form a galvanic pair, which would in turn speed up the corrosion process of the weaker material. Consequently, the formation of a galvanic pair should be avoided. Welding of two different steel alloys also hinders the quality of the weld and as such the alloy of the sealing plates as well as the filler material should be carefully chosen. Since the hermetic sealing is crucial for the long-term safety of the disposal, ultrasound or other non-destructive inspection is performed on the welds to ensure their quality. Radiological weld inspection methods such as X-ray cannot be utilized for these welds, as the strong gamma radiation from the RPV can disturb the inspection.

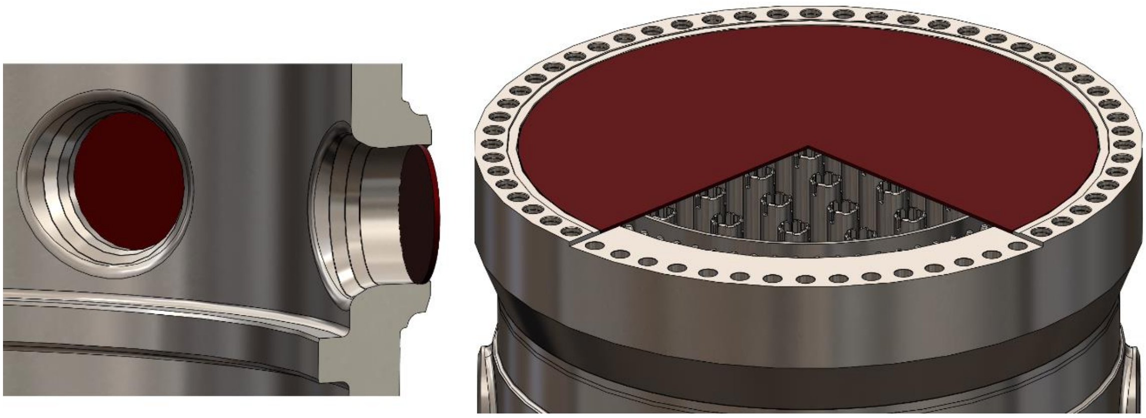

Figure 2. Stainless steel sealing plates (red), the nozzle plates on left and the top plate on right.

While the thickness of the stainless steel plates is just a fraction of the RPV walls, the corrosion rate for stainless steel in anaerobic conditions is generally one order of magnitude lower than that of carbon steel, which justifies the 20 mm plate thickness (Nummi, 2019).

The RSC used to transfer the RPVI is not large enough to fit on the RPV, so the RPV must be fitted with a custom-made radiation shield when it is transported to the waste repository. The shield utilized here follows the design principles of the original decommissioning plan, so the previous MCNP-models (Oinonen, 2018) made of lifting of the RPV will still be representative. However, a modification was made by fitting the radiation shield more tightly around the RPV, to eliminate radiation scattering from a gap between the shield and the

RPV. The radiation shield consists of two cylinder halves with 60 mm of steel and 240 mm of concrete, which are joined together with eight 70 mm bolts on both sides of the RPV.

The RPV radiation shield is remotely installed around the RPV support flange, utilizing a support structure built around the reactor pit. The shield is installed in its place right after the RPV is lifted from the reactor pit to the +25.40 level, the bolts can then be tightened manually as the radiation levels are decreased by the shield (Oinonen, 2018). The halves of the shield and the lifting tool weight 23.2 and 20.9 tons a piece respectively, which makes the total weight of the package 267.8 tons. Even though this marginally exceeds the maximum capacity of the polar crane, the lift should be possible to carry out. The closure of the RPV shield is presented in Figure 3.

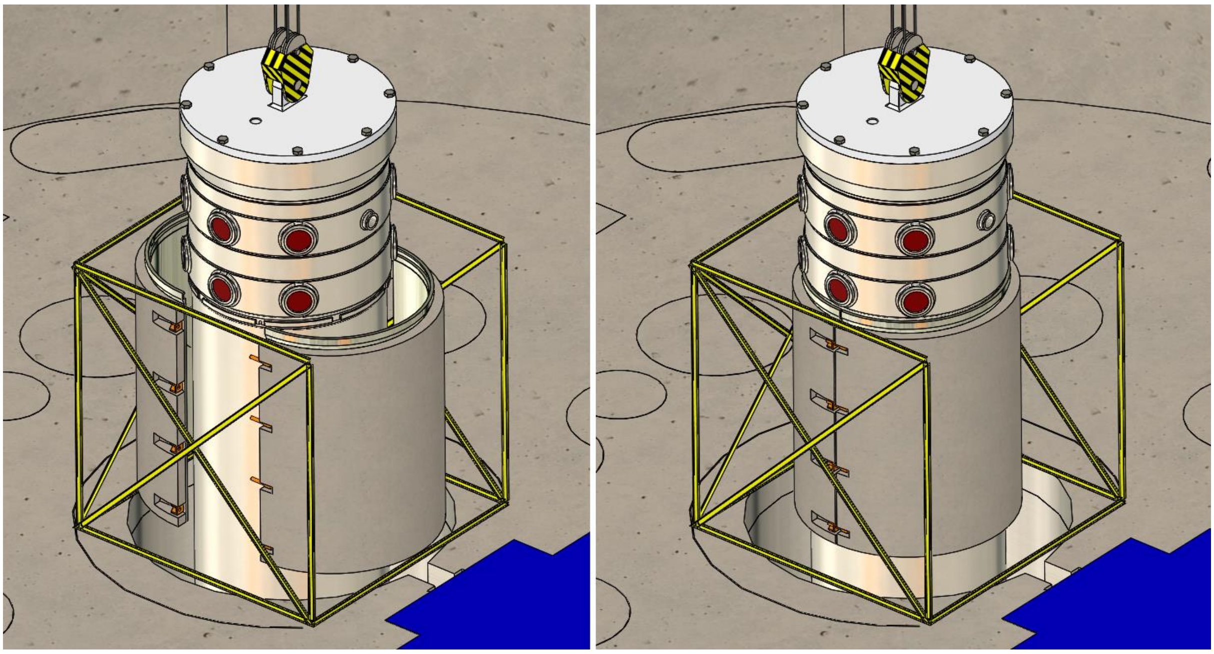

Figure 3. The RPV radiation shield closure process.

The RPVI are lifted inside the RSC as during the maintenance outages. However, when the RPVI are transported to the waste repository, the cylinder will be rotated to a horizontal position. In order to prevent a radiation cone from being directed out of the bottom of the cylinder, it will be outfitted with an additional 200 mm thick steel bottom plate.

The shield elements and control rods are packed inside a transportation package, that is made out of 200 mm thick steel and houses a maximum of 40 pieces of said elements or rods. The same package is used as a final disposal package in the segmentation decommissioning option and the details of the package are presented in chapter 5.3.3. Packaging is done either in the reactor hall or in the used fuel storage, depending on where the shield elements are stored after the reactor has been shut down.

5.2.2 Transportation

The packed RPV is lowered down to the mobile platform, which moves on rails supported by the gantry on the assembly area on level +10.45. The RPV is lowered in a vertical position and a corner of the radiation shield is rested on steel cables connected to a lift device capable of supporting the package weight, from where the RPV is gradually lowered into a horizontal position. Tilting of the RPV package is presented in Figure 4.

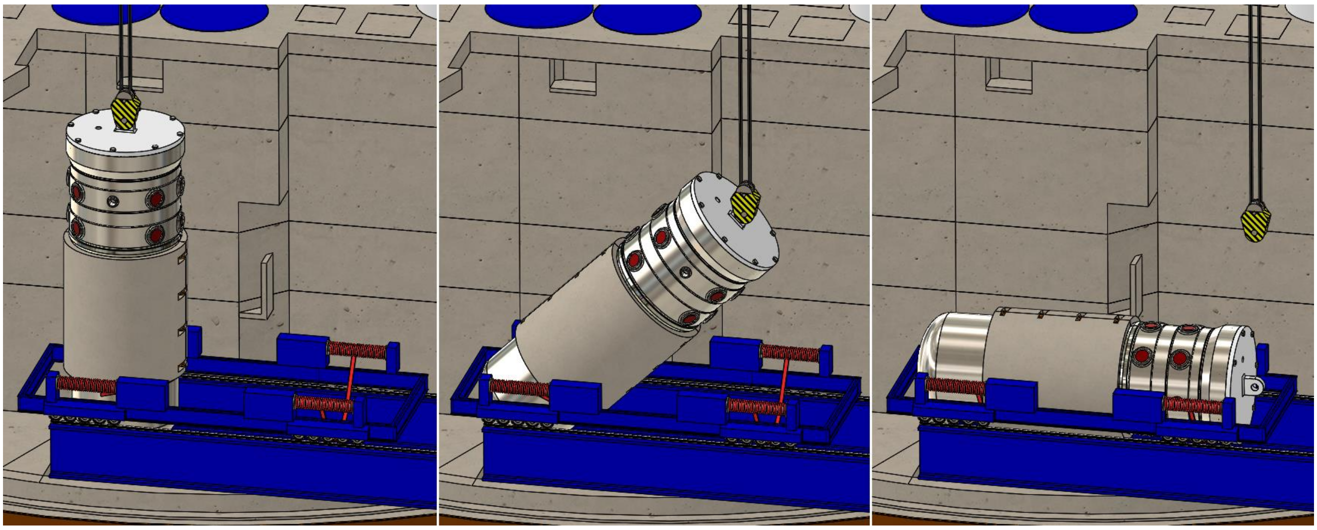

Figure 4. Tilting of the packed RPV with the polar crane onto the mobile platform.

The mobile platform is used to take the RPV out from the containment building, after which it is lowered to the SPMT on the ground level using the lift device (Figure 5). The height of the final transport is 6.3 m, it is 5.0 m wide on the location of the radiation shield and length of the SPMT is 14 m. These dimensions fit the waste repository access tunnel with large margins. Total weight of the RPV, radiation shields and the SPMT is 310 tons, which is less than the 350-ton (Kelokaski, 2020) design basis of the waste repository access tunnel.

The yard area however is not designed to support such heavy transports, so the point weight of the transport could be too heavy for it, as there is multiple maintenance tunnels and the main coolant tunnel running under the yard area. In which case a second SPMT platform could be utilized to even up the weight to larger area or the yard structures could be reinforced, if a second SPMT platform is used the package is required to be moved to a single SPMT before entering the repository.

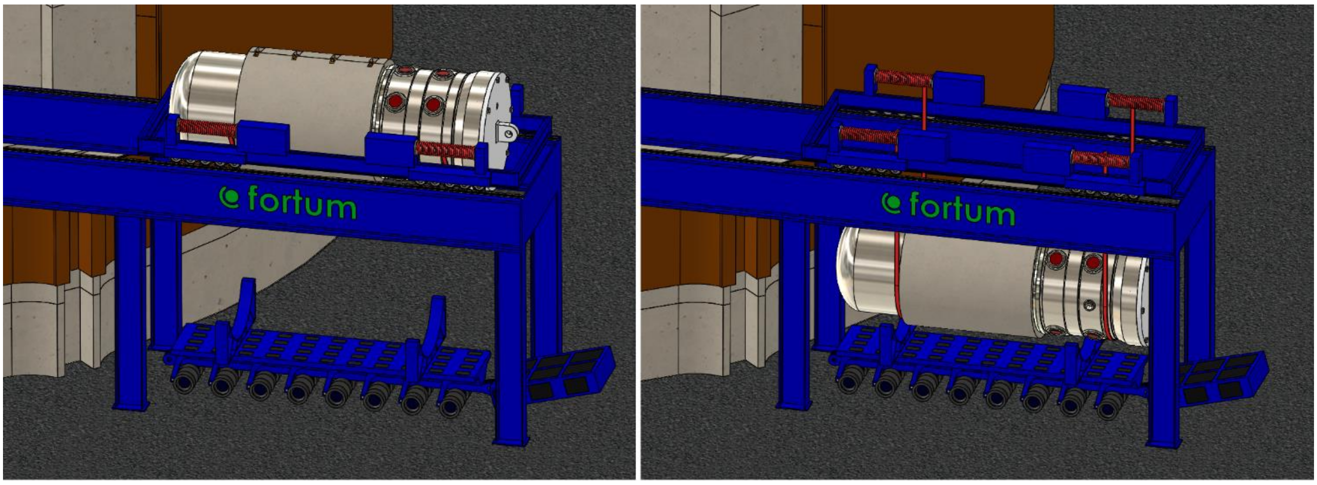

Figure 5. Lowering the RPV to the SPMT on the ground level.

The SPMT is utilized to transport the RPV package to the waste repository on level -110.00. The total length of the transport route is approximately 1.5 km.

The RPVI follows the same work order as the RPV, but instead the RSC containing a single RPVI component is transported, and the transportation process is simply repeated returning the RSC to the reactor hall between each step. The RPVI are transported to the waste repository in the order of placing them inside the RPV, so the barrel is transported first, followed by the barrel bottom, the core basket and finally the PTU. The height of the transport with RSC is 5.7 m, width 4.1 m and the length of 14 m is defined by the SPMT. The heaviest transport is the barrel, together with the RSC and the SPMT the total weight of the transport is 261.3 tons.

The shield elements and control rods are transported to the waste repository in their S3-transport package utilizing the same SPMT unit as with the RPV and the RPVI. The shield elements and control rods are transported to the waste repository and positioned inside the RPV after the core basket has been transported, but before the PTU. As the capacity of the S3-transport package only allows 40 elements to be transported, a total of nine shipments are required.

5.2.3 Waste repository

In the waste repository the RPV will be placed inside a silo excavated to the bedrock for this purpose. Before lowering the RPV to the silo, a concrete support structure is cast on the bottom, which will hold the RPV on its place by supporting the radiation shield bolted on the RPV. The RPV is sled into the silo utilizing a hydraulic jacking system and a roller that will support most of the weight. After the RPV has been lowered to the concrete support, the remaining free space around the RPV is filled with crushed concrete and three lateral concrete supports are cast around the top flange. This will ensure that the RPV will not move when the RPVI, the shield elements and control rods are loaded in. The work process and final placement of the RPV is presented on Figure 6.

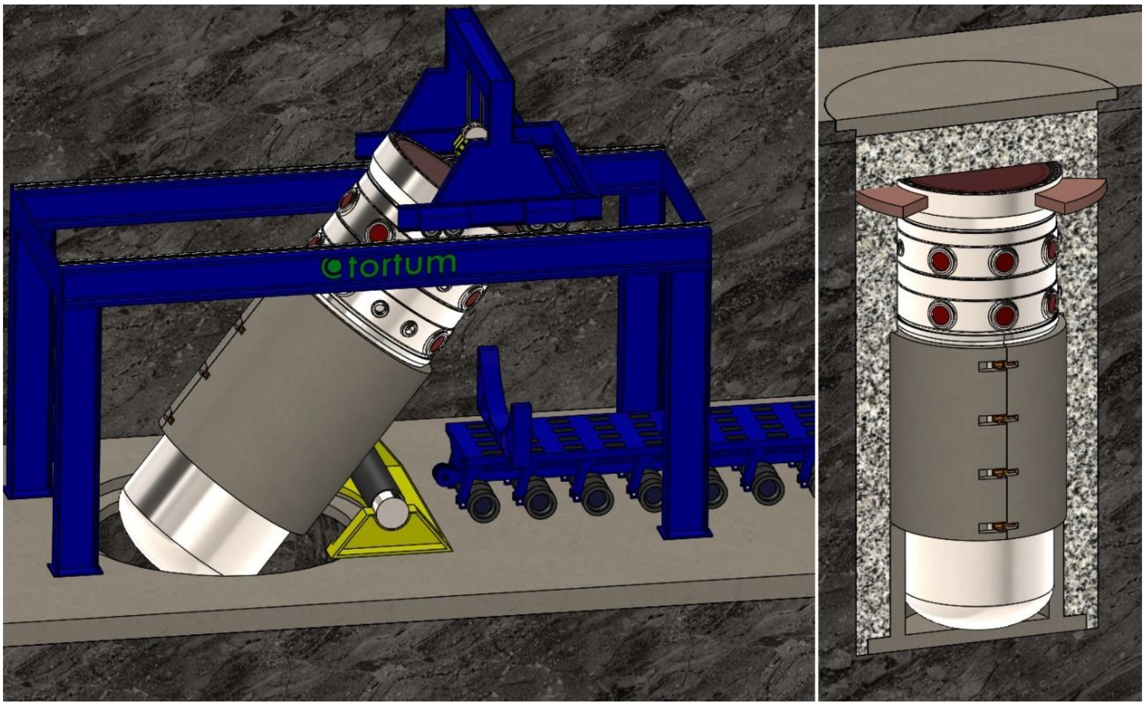

Figure 6. Hydraulic jacking system in the waste repository and final placement of the RPV inside the disposal silo.

The RPVI are loaded inside the RPV using the same hydraulic jacking system and rolling support as with the RPV. After the core basket has been loaded in, the shield elements and the control rods can be loaded on their positions. Loading should be done in such a way that the activity of the elements is spread as much as possible, which will help with heat dissipation of the decay heat.

After the RPV has been placed into its silo and the RPVI have been placed inside it, the remaining empty space is filled with concrete. Concrete filling will keep the conditions inside the vessel alkaline, which in turn slows down corrosion of the components and the concrete itself hinders the release of the radioisotopes. If a stainless steel lid is to be welded on top of the vessel, the total amount of concrete required is 101.5 m^3 and if the vessel head is used instead, it also needs to be filled, which requires another 9.5 m^3 of concrete. To make sure that the concrete fills the cold side of the RPV, six openings need to be cut on the barrel of the reactor just below the hot/cold-side sealing (Figure 7). This cutting operation should be done before the rest of the RPVI are placed inside to minimize the radiation doses.

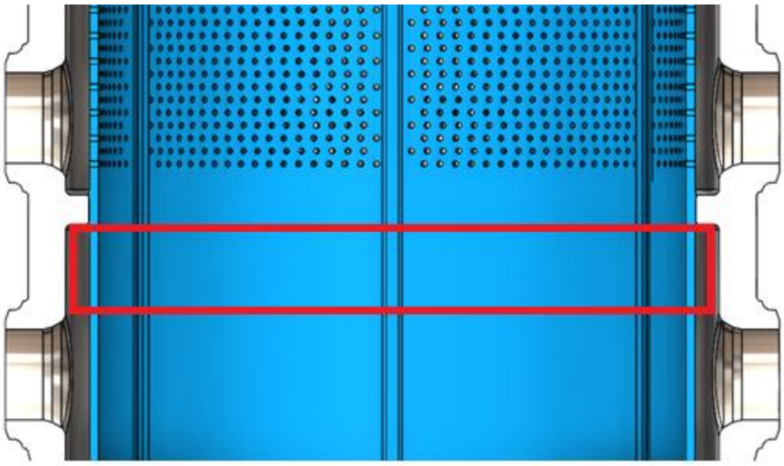

Figure 7. The concrete pouring opening locations on the barrel.

Concrete used in filling the RPV can be the same quality as what is used in filling the intermediate waste cavern basin. This concrete should be agile enough to fill the RPV thoroughly while being coarse enough to prevent the divergence of water. However, the concrete pouring of the RPV should be done in at least four stages, as the water could start to diverge in such a high cast. Before the pouring is done, the concrete solution should be tested on a heated testing rig with pipes of equal diameter of upper and lower core plate holes, to ensure that the concrete does not clog the openings when it is poured. (Rämö, 2021.)

The RPV is finally sealed by welding a 20 mm thick stainless steel plate on top of the vessel. The plate is welded on the stainless steel cladding of the RPV as presented in Figure 2. A steel plate is used instead of simply bolting on the vessel head, as long-term safety of bolted closure could not be estimated. Welding of all the openings of the vessel head was also deemed to pose a higher risk of initial weld defects and welding the vessel head to the RPV with a good quality weld was estimated to be challenging. Weld quality of the plate is to be inspected with the same accuracy and methods as the nozzle plates.

There is one downside in replacing the vessel head with a stainless steel plate, as the top most 790 mm of the PTU shell and the instrumentation tubes are required to be cut off. The PTU shell can be removed with one cut while the instrumentation tubes need multiple small cuts. This can be done only after the PTU has been transported to the waste repository, as cutting the shell will also remove the lifting openings used to lift the PTU. While at this point the RPV will already contain most the activity to be disposed of, the overall radiation levels can be lowered significantly by pouring the fill concrete before the cut is made. As the top part can be estimated to be only slightly contaminated, the cut can be done with a plasma cutting device when good ventilation of the cutting fumes is taken care of, consequently the removed part can be disposed of without any further packaging considering long term safety.

Finally, the top of the RPV is covered with crushed concrete and a concrete lid is installed to cover the silo. This lid is sealed with grouting concrete. The final position of the RPV is presented in Figure 6.

5.2.4 Decay heat

When the RPV and the RPVI are disposed of without segmentation, all the decay heat generated will be transferred from inside the RPV to the surrounding bedrock. The decay heat generated will total up to 8.7 kW. An ANSYS Fluent simulation of this case shows that the internal temperature of the RPV will increase up to 100 – 140 °C and it's possible that the outer shell of the RPV will heat up to 100 °C in 200 days after closing the RPV (T.Toppila, 2003)

The decommissioning plan presented in this thesis also suggests that the control rods would be disposed of inside the RPV, which is not included in the previous simulation. The effect of adding 1.5 kW of thermal power inside the RPV is not estimated with simulations, but rough linear estimation would suggest that the temperature would not increase problematically.

The heat generated will possibly boil water outside the RPV, although the boiling point of water will be increased considerably while the pressure rises to around ten bars after the waste repository fills with ground water. Before the repository is filled sufficient pressure outlets are required for the silo to prevent damage to the concrete shell and lid. The inside temperature of the components will affect the concrete filling of the RPV, and the fill pour should be tested to make sure that the concrete will not dry while it is being poured. However, as the concrete inside the RPV won't have any structural strength requirements, small cracking caused by the heat while the concrete is drying will not be a problem.

5.2.5 Schedule

Scheduling of RPV removal without segmentation was done in Microsoft Project Professional and in total the time estimate is around 250 workdays, when working with one eight-hour shift per day. The schedule estimation was done based on earlier work (Kälviäinen, 2018) with updated decommissioning work stages presented here. Durations of major work stages are presented in Table 3.

Table 3. Major work stage durations of no segmentation decommissioning option.

Work stage	Duration [d]
The RPV	124.5
The RPVI	76.75
Shield elements	27.5
Control rods	27
Vessel head	31
Sealing the RPV silo	6.5
Total	**255.75**

5.3 Segmentation of all components

In this decommissioning option the RPV and the RPVI are segmented in pieces and packed to steel final disposal caskets inside the containment building, from where they are then transported and placed in the DWH1. In this chapter different segmentation methods used in nuclear decommissioning are discussed, a preliminary segmentation plan is presented based on the created CAD-models, and possible options are presented for how the work stages could be performed during the decommissioning.

5.3.1 Segmentation methods

A wide variety of different cutting methods for metal components and structures exist, while only some of them are proven to work in a NPP environment. In this chapter, some operation basics of these cutting methods are discussed as well as their advantages and disadvantages. Special attention is paid to the cutting methods that would be best suited for segmentation of the RPV and the RPVI of Loviisa NPP and are tested in other decommissioning projects earlier, i.e., are proven tech in NPP decommissioning. In the last part of the chapter a comparison table of the performance properties of different methods is presented.

As segmentation methods in nuclear decommissioning are used to cut radioactive or contaminated materials, many aspects of the cutting process should be considered with additional care. The waste generation of the dismantling method should be minimized, and the spread of contamination must be prevented wherever possible. In principle, the smaller the cutting waste is, the harder the prevention of contamination is, e.g., cutting methods that generate aerosols as by product should be avoided, if proper air ventilation and filtration cannot be utilized. And even when they are utilized, the aerosol contamination will contaminate everything inside a hermetically sealed containment and any filters used will add to the radioactive waste amount generated. When cutting components underwater water clarity and filtration should be considered carefully, as they may be the most difficult factors to manage when cutting components underwater (EPRI, 2001). Mechanical cutting methods are typically best suited for this type of operations, as they generate only small amounts of aerosols and fine dust generation is more manageable. Other aspects to consider are cutting speed and maintenance frequency, which directly affect the radiation doses accumulated and costs of the work done. (Lainetti, 2011)

Oxygen burning

Oxy-fuel cutting is one of the oldest and most efficient ways to cut thick steel. Oxy-fuel cutting is based on exothermic chemical reaction between the cut material and oxygen, the reaction is self-sufficient but requires activation energy in the form of acetylene flame or equivalent. Oxy-fuel cutting is well suited for ferritic steels but struggles with austenitic steels. However, when cutting through a combination of these, like the RPV cladding, the heat from the ferritic steel smelt enables the cutting of the thin austenitic steel cladding. This ability can also be achieved by adding metal powder to the oxygen stream, this will however increase the produced contamination excessively. (European Commission, 2009)

Electric cutting methods

Plasma arc cutting is currently the most widely used technology when cutting odd shaped components. The technology is based on flow of high electric current. It works similarly to oxy-fuel cutting, but instead of a chemical reaction the heat is generated by direct current arc from tungsten electrode, which ionizes gas to its plasma state that is then blown to the cut material melting it. This conductive plasma can be manipulated by pneumatical air flow or by utilizing magnetic fields. Plasma arc cutting can also cut through austenitic steel alloys. (European Commission, 2009)

Electric discharge machining technology utilizes high voltage low current sparks from an electrode to melt the cut material. There are a few different applications of electric discharge machining technology in the manufacturing field, but within nuclear decommissioning only contact arc metal cutting has been utilized so far. Instead of high voltage sparks, in the contact arc metal cutting voltage is transferred via low voltage plasma arcs, while a high velocity water stream is used to direct the arcs position and to remove the slug generated. Shape of the cutting electrode is commonly sword like, and it is fabricated of graphite or carbon fiber reinforced graphite. The contact arc metal cutting is best suited for complex hollow structures such as PTU pipes and instrumentation fixtures. (European Commission, 2009)

Laser beam cutting

Laser beam cutting is based on high powered coherent light beam, which focuses a high amount of energy on one spot. In comparison to other thermal cutting methods, laser offers higher accuracy and lower contamination production. Also, the nozzle of the laser beam doesn’t need to be situated next to the cut material, which gives some more flexibility when cutting complex shapes. Lasers however require lot of operating power and are quite expensive investments, while easily achievable cutting thickness can be somewhat limited. Laser cutting is not yet utilized in nuclear decommissioning, but wide use of it in other fields as well as benefits listed, make it an interesting cutting method that could be considered in the future.

Mechanical shear

Mechanical shearing utilizes high powered hydraulic claws to either cut or tear components in pieces. Advantage of this is that no separate contamination is produced, and all the dismantled components are comparably large and therefore easier to clean out. This method is however limited on terms of cutting thickness, as thick steel components would require large claws. Shearing would be best suited for clearing of instrumentation installation and could be possibly coupled with manipulator arms used for handling the components.

Mechanical saws

Mechanical saws are versatile and a tested method for metal dismantling. Many different saw types for different purposes exists. In general, all saws produce some amount of contamination in the form of metal shavings, but they will not produce much aerosol contamination. Saws also add some amount of contaminated waste, as used blades, bands and wires must be often disposed of as LILW.

Abrasive cutters

Abrasive water suspension jet cutting is based on high pressure water stream, with added abrasive material to grind metal alloys. In comparison to thermal cutting methods, an abrasive water suspension jet produces only a small amount of aerosols, but the amount of total cutting waste is increased as the abrasive material will be contaminated. The used water can however be recycled, and the amount of liquid waste can be held at a minimum. (European Commission, 2009)

Comparison

Table 4 lists different cutting depth, speed and the estimated contamination generated of the different cutting technologies discussed in this chapter. All the cutting technologies are able to perform under water, as this is sometimes required while handling components with excessive activity. However, only the mechanical cutting methods are directly suited for this and other methods require some additional arrangements. Mechanical cutting methods are also the only ones that will not produce contaminants in aerosol form, so they are the only ones that are safe to use without a hermetically sealed and well filtered ventilation system. There are various different applications of mechanical saws and it is therefore impossible to give a good estimation of cutting speed for them. Overall, it can be said that the speeds are lower than with any other method.

Table 4. Segmentation methods comparison (European Commission, 2009; Juyoul & Batbuyan 2020; Esab, 2021).

Technology	Contamination / cutting waste	Aerosol contaminants	Depth of cut [mm]	Cutting speed [mm/min][3]	Cutting speed [mm/min][4]
Oxy-fuel	High	High	25 – 800	350 – 700	100 – 125
Plasma arch	High	Medium	150	100 – 500	150
Contact Arc Metal Cutting	Medium	Medium	270	1500	–
Abrasive Water Jet	High	Very low	300	200	70 – 100
Mechanical saws	High	None	–	–	–

[3] 10 mm sheet metal.
[4] 200 mm sheet metal.

While the mechanical saws are often the slowest cutting methods, they offer one distinctive advantage over thermal ones, abrasive and electrical cutting methods. As they can be utilized to segment multi-layered components, such as the core basket with one single cut. Even though the mentioned cutting methods can cut steel up to a thickness of several hundred millimeters, they require a channel to keep the cutting smelt, plasma or waterjet together. So, if the structure of the cut component consists of different thin layers of steel, only mechanical saws can be utilized to cut through them all at once, while other methods require multiple cuts performed from different directions.

5.3.2 Segmentation

The following preliminary segmentation plan was done for the RPV and RPVI. The plan is based on the CAD-models and the activity inventory of the components. The main assumption considering the activation of the components was that most of the activity is accumulated near the core region of the RPV and that these parts are required to be cut and handled separately from the rest. As there is no exact vertical activation data available, a rough estimation was made that structures within half meters from the upper and lower core plates would contain high levels of activity. These parts would then be segmented under water and packed to more robust containers with adequate protection from radiation.

As the reactor can be horizontally divided roughly in three similar segments, most of the segmentation follows a pattern where three identical cuts are made. This will result in components being cut to closely equal 60° slices. Example segmentation scheme of the core basket is presented in Figure 8 and the rest of the RPVI and vessel head are presented in Appendix 2.

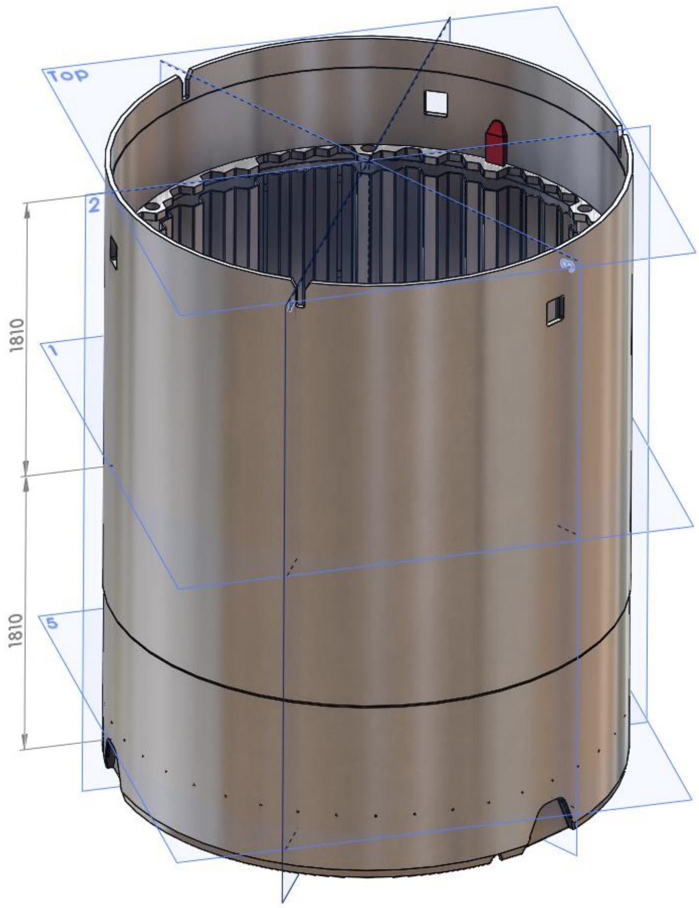

Figure 8. Segmentation scheme of core basket, where three vertical and two horizontal cuts are made.

Best location for the segmentation and packaging of the RPV and RPVI is in the reactor hall, with some modifications to existing structures and addition of new temporary structures. The most limiting factor in the choice of the location is that the current access routes from the containment building limit transportation of the large components outside. The reactor hall also offers some benefits as existing systems such as the polar crane can be utilized during the segmentation process and the reactor pit is easy to fill with water. The spread of contamination can also be more easily supervised when the components are cut inside the containment building.

To further mitigate the contamination spread, a temporary hermetically sealed containment structure is built on top of the reactor pit on the +25.40 level, which will house the RPV and RPVI dismantling and packing systems. This structure will isolate the reactor pit from the rest of the reactor hall so that cutting methods that generate contaminated aerosols can be utilized in the dismantling process. The containment is equipped with air ventilation and a filtering system that keeps the structure in a negative pressure. The temporary containment is equipped with a top hatch, so that the polar crane can be used to lift the large components to the reactor pit and lift the ready waste packages out of the reactor hall. The segmentation setup is presented in Figure 9.

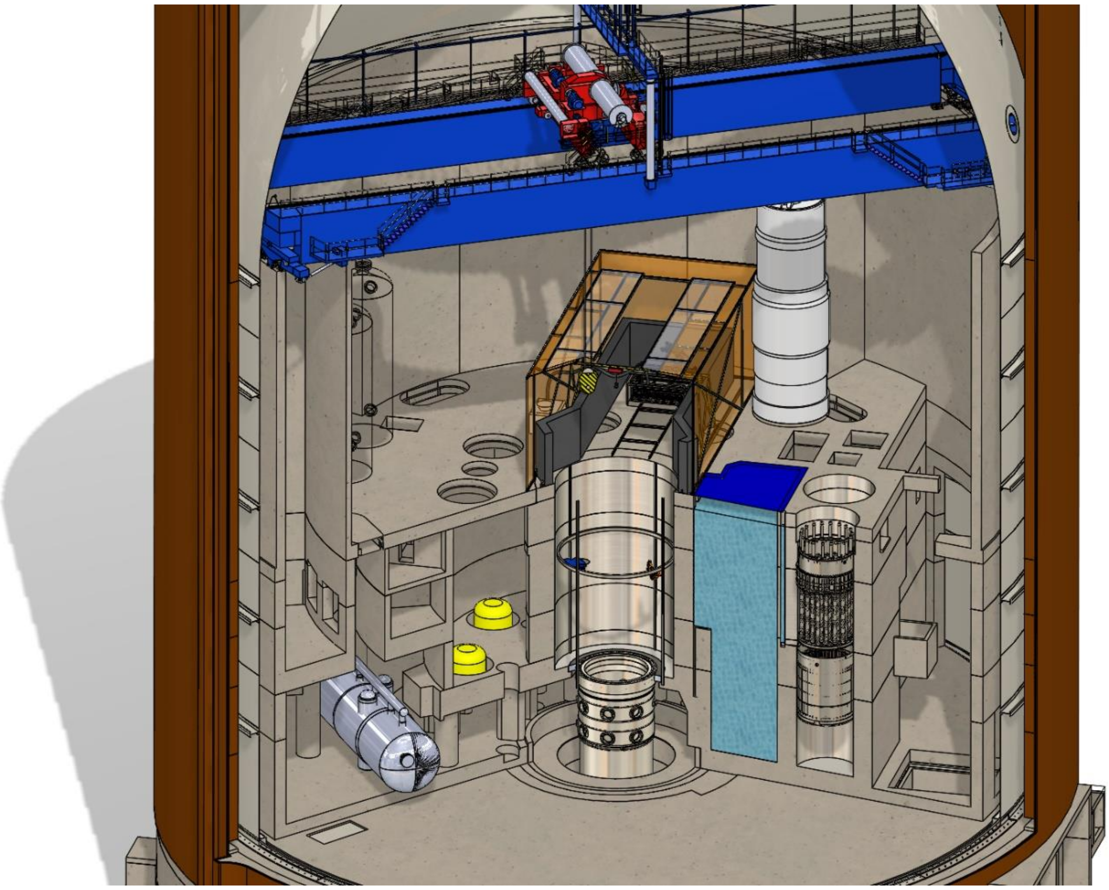

Figure 9. Loviisa temporary containment structure with segmentation and packing capabilities built inside the reactor hall.

The segmentation station will be built in the reactor pit inside the temporary containment building. The equipment required for cutting and manipulating the parts will be installed on a circular rail, which will in turn move vertically on rails installed on the reactor pit walls. This will enable a good range of usage for all the tools used, without the need for moving large pieces of the components being cut. The tools required for the segmentation include:

- Cameras for monitoring the cutting tasks.
- Direct ventilation system for removing the majority of the cutting fumes.
- Robot arms with different tools attached on them, manipulator claw, gripper claw, jigsaw, drill, oxy-fuel and plasma cutting devices. Some of these can be made interchangeable, depending on the component being dismantled.
- Disc, band or rope saw installation.

The floor level of the temporary containment building will house the packing station. Packing station will include a crane for lifting the cut parts out of the reactor pit and into the waste packages, robot arm to help position the cut parts inside a waste package, concrete pump for filling the highly active waste packages with concrete, welding station for welding the waste packages remotely, and rails for moving the waste packages from filling to welding. The packing station as well as the reactor pit will be surrounded by radiation shielding wall, so that the radiation emitted from the parts can be limited inside the packing station. Packing of the waste packages will be discussed with more detail in chapter 5.3.3.

To keep the dismantled component in place and to prevent cutting scrap from spreading outside the reactor pit e.g., into the RPV, a multipurpose support platform (MPS) will be installed in the bottom of the reactor pit as displayed in Figure 10.

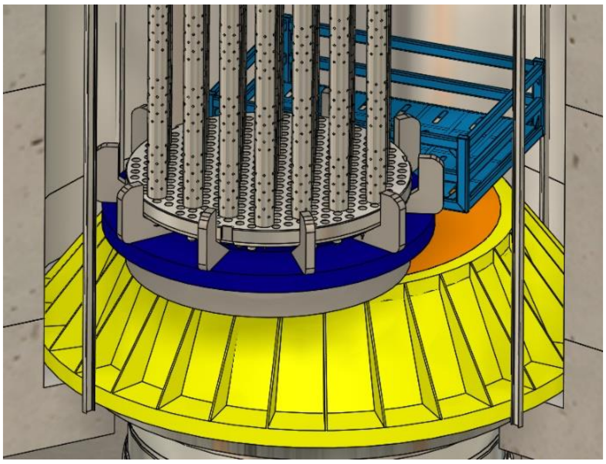

Figure 10. Multipurpose support platform installation in the reactor pit.

For the RPVI segmentation the MPS will be equipped with a turntable for the dismantled component, a separate platform for a packing basket and an opening in the middle of the platform, which is covered with a plate. These baskets will be utilized when dismantling the components that were located next to the core region, so that highly activated parts can be lifted out of the reactor pit as one set and packed inside the steel packages as fast as possible. When the RPV is dismantled, the turntable, the basket platform and the middle cover plate are removed, so that the RPV can be lowered on the MPS.

RPVI

The RPVI materials that have been located in the core region during reactor operation have accumulated so much activity, that additional radiation protection measures must be taken when these components are being dismantled. These highly activated materials include the core basket, middle and bottom part of the barrel, bottom core plate of the PTU and top core plate of the barrel bottom. While these components are being segmented, the reactor pit is filled with water up to the level +22.00 and the segmentation is done mostly using mechanical tools, that are well suited for underwater working conditions.

To minimize the risk of contaminating the least activated components with the highly activated ones, the component segmentation will be done in the following work order:

- The barrel bottom is lifted from well two to the reactor pit and then segmented and packed.
- The barrel is lifted from the well two to the reactor pit and then segmented and packed.
- The PTU is lifted from well one to the reactor pit and then segmented and packed.
- The core basket is lifted from well one to reactor pit and segmented and packed. (EPRI, 2001)

The segmentation can be somewhat optimized by temporarily lowering the water level in the reactor pit while the segmented components allow this, this could be possibly done with the top part of the PTU, the top part of the barrel, and the bottom part of the barrel bottom.

After all the RPVI components have been dismantled the reactor pit is cleaned from any cutting scraps left behind, which are then packed to the last core basket waste package. Thorough decontamination of the reactor pit is not necessarily worthwhile at this point, as the dismantling of the RPV will be commenced in the next phase. However, some decontamination actions may be required, if the activity levels would prevent preparatory work inside the reactor pit.

RPV

After the RPVI are dismantled and transported to the waste repository, the process for RPV dismantling can be commenced. The segmentation of the RPV will be done inside the reactor pit, as again this is the optimal place to restrict the spread of contamination and minimize the radiation cones to the reactor hall.

The MPS is lifted out of the reactor pit to the reactor hall using the polar crane. The turntable, the basket platform and the middle cover plate attached to it are then removed. Now that the RPV is exposed the thermal insulation is removed, the nozzles of the RPV are cut and the RPV support structures are dismantled as described in chapter 5.1.2. The 180 mm lifting tool is then attached to the RPV using the vessel head bolts and the RPV is lifted out of the reactor pit using the polar crane. The RPV is then lowered to the loading pool so that the core region of it is covered and temporary supports are installed through the nozzle openings to keep the RPV in position, while the polar crane is detached. While the RPV is parked in the refueling pool, the multipurpose support platform is installed back to the bottom of the reactor pit and equipment required for the RPV segmentation are prepared inside the temporary containment structure.

Alternatively, the MPS could be designed so that it can be opened and closed remotely, allowing it to remain in the bottom of the reactor pit while the RPV is lifted out. This would eliminate the need to place the RPV inside the refueling pool, as the polar crane would not be required for the installation of the MPS. The advantage of this strategy would be that the refueling pool would not need any modifications for the dismantling of the RPV and the used fuel elements that are cooling in the pool would not have to be removed before the decommissioning can begin.

The RPV is lifted back to the reactor pit, the polar crane is disconnected, and the temporary containment structure is sealed hermetically. The RPV segmentation follows the same principle as the RPVI, the RPV is horizontally segmented as per Figure 11 and the horizontal segments are divided into six equal pieces. Segmentation is done utilizing either oxy-fuel or plasma torch and the cut pieces are lifted to the waste packets using either a hydraulic or a magnetic catch. To minimize aerosol contamination, direct cutting fume extraction will be utilized. The activity of the RPV does not require water filling of the reactor pit, but when the core region of the RPV is being segmented, additional caution to radiation should be considered.

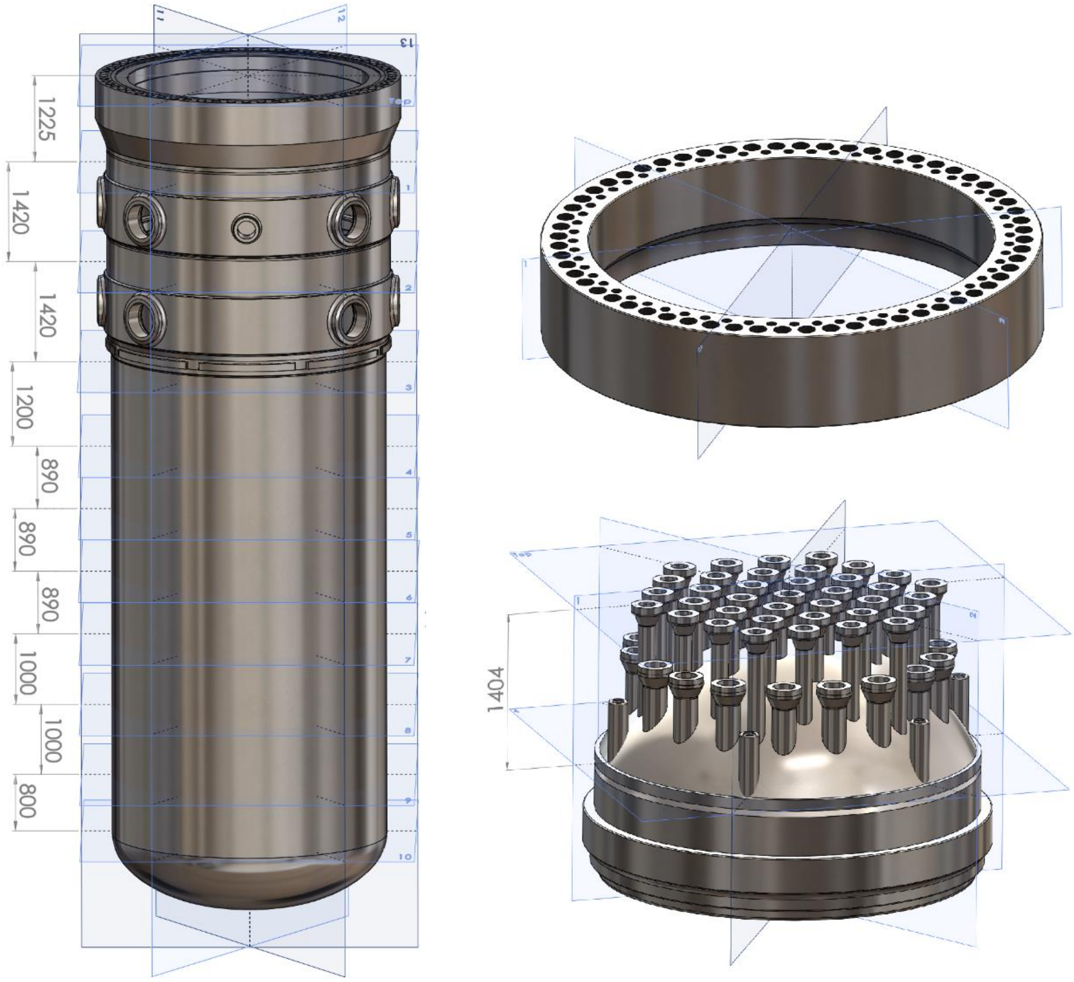

Figure 11. Segmentation schemes of the RPV, vessel head and the upper flange.

Next the vessel head and the upper flange of the RPV are dismantled. First the vessel head inlets for control rods and instrumentation are disconnected. A round fraction with a diameter of 1 700 mm is cut from the top of the vessel head, while rest of the component is cut horizontally in two and vertically in six equal pieces. Upper flange and sealing ring below it are cut vertically in six equal pieces.

After the RPV has been completely segmented, the reactor pit can be again cleaned from the cutting scraps and they can be packed into the last waste package. The reactor pit is then thoroughly decontaminated, and all temporary structures are dismantled and treated as LILW as the aerosols from the cutting process have certainly contaminated them.

5.3.3 Packaging

Segmented parts will be packed into S2-steel packages, with different wall thicknesses based on the activity of the contents. While the long-term safety also requited thick packaging, the thickness required by sufficient radiation protection exceeds this requirement. However, to fulfil long-term safety durability requirements, the active packages will be welded shut with a weld thickness of at least 100 mm. This welding thickness is also still reasonably easy to complete with submerged arc welding technology and no complicated welding equipment is needed (Nikula, 2020).

In total, there are three different S2-containers varying in casing thickness: 50 mm, 100 mm and 200 mm, for which the dimension and masses are presented in Table 5. All the containers share the same outer dimensions so that handling and storing them can be arranged easily. In addition, there will be a S3-package for the shield elements and control rods, like the heaviest S2-package the casing will be 200 mm thick, and the container can house 40 shield elements in vertical position. To keep the elements in place, the container will have fuel element sized slots where the elements can be lowered into position.

Table 5. S2/3-package dimensions and masses.

Package	Length [m]	Width [m]	Height [m]	Mass [t]
S2-Outside	3.4	2.6	1.3	-
50	3.3	2.5	1.2	15.2
100	3.2	2.4	1.1	24.2
200	3.0	2.2	0.9	44.0
S3	2.5	1.4	3.65	45.8

As the RPVI with the highest activity will be segmented under water, a steel basket will be utilized inside the 200 mm containers so that all the segmented parts can be lifted directly to the container in one go (Figure 12). This will minimize the accumulated dose of the workers when the parts are lifted out of the water.

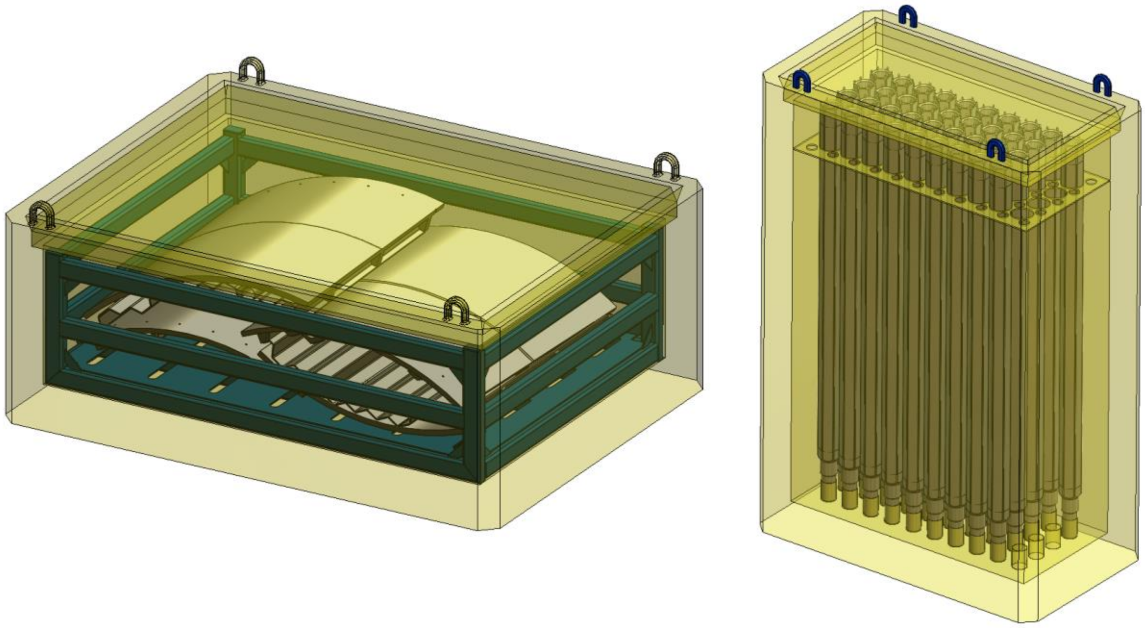

Figure 12. On the right four pieces of the core basket placed in a lifting basket inside a S2-200 package and on the left a S3-package filled with 37 shield elements.

The optimal way to position the parts (curved cylinder segments) into a package, is so that their in core facing side is facing the bottom of the package. This will direct the strongest radiation cone downwards and the rest of the component will offer some extra shielding upwards.

The segmented parts were modelled and visualized inside the containers by utilizing Physical Dynamics in Solidworks, in which the program identifies the physical dimensions of the parts and they can be then dragged around the assembly model while Solidworks models how they will interact with other components in the model. This method enabled modelling the containers with realistic packing density, as the segmented parts could be easily situated inside the packages, while the program took care that the parts will not intersect with each other. The total amount of packages required for one reactor unit is presented in Table 6.

Table 6. Number of S2-packages required per reactor unit.

Part	S2-50	S2-100	S2-200
Core basket	-	-	4
PTU	3	-	1
Barrel	1	-	2
Barrel bottom	2	-	1
RPV	8	3	-
Vessel head	4	-	-
Total	**18**	**3**	**8**

In addition to the S2-packages, the estimated amount of 145 shield elements per reactor unit (Lehtinen, 2021) and a total of 367 control rods (Mayer, 2008), will require a total of eight S3-packages for the shield elements and ten S3-packages for the control rods.

5.3.4 Transportation and locating the packages

Waste packages accumulated from the RPV and the RPVI dismantling can be transported to the waste repository by utilizing existing lifting equipment at reactor hall and a remote controlled SPMT. The example segmentation and packing scheme used here will require a space of ~11 meters of the length of the DWH1. (Figure 13) The packages are situated in the DWH1 in such a way that the packages that contain most of the activity are covered by the packages with lower activity. This will offer some extra radiation protection for the staff while the rest of the DWH1 is filled.

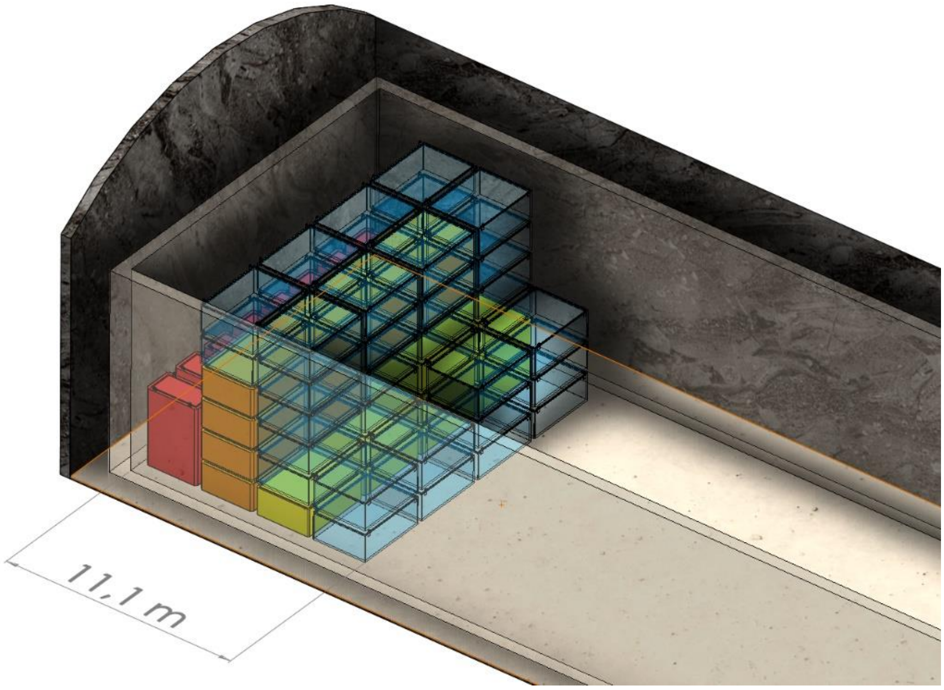

Figure 13. Waste packages of both units located in the back of DWH1. S2-200 (orange), S2-100 (yellow), S2-50 (blue) and S3 (red).

5.3.5 Decay heat

When the RPV and the RPVI are dismantled and packed inside the metal packages, the decay heat generation will be distributed between the packages and will not reach as high levels as when the internals are placed inside the RPV. To estimate the temperature of the package surfaces and the air of the DWH1 an ANSYS Fluent model of the package layout was done. The Fluent simulation was done using the same densities, heat transfer coefficients and reference temperature of the bed rock as with the simulation of the whole RPV (Toppila, 2003). The DWH1 was assumed to be still filled with air to see if the working conditions would change during the filling of the waste repository. This air space was however assumed to be isolated from rest of the waste repository to represent the possible limited air conditioning of the DWH1.

For this purpose, only the packages with a heat generation higher than 30 W were modelled. The highest heat generation was from the shield elements with 1 363 W/package. The model was also simplified to two dimension and the components inside the packages were represented only as heat generating steel rectangles surrounded by concrete and the package itself. To make the estimated temperature evolution more conservative, the packages were situated on top of each other to prevent proper airflow around them and the heat generation power loss from decay of Co-60 during the storage period was not considered. The simulation was run for a total of 1 000 days with one day timesteps and the temperature evened out to a stable value after 400 days. As seen from Figure 14, the highest temperature inside and between the packages evens out to ~80 °C. While this is still considerably high, the packages will not increase the air or wall temperatures of the DWH1, which stay near the 10 °C during the whole simulation period.

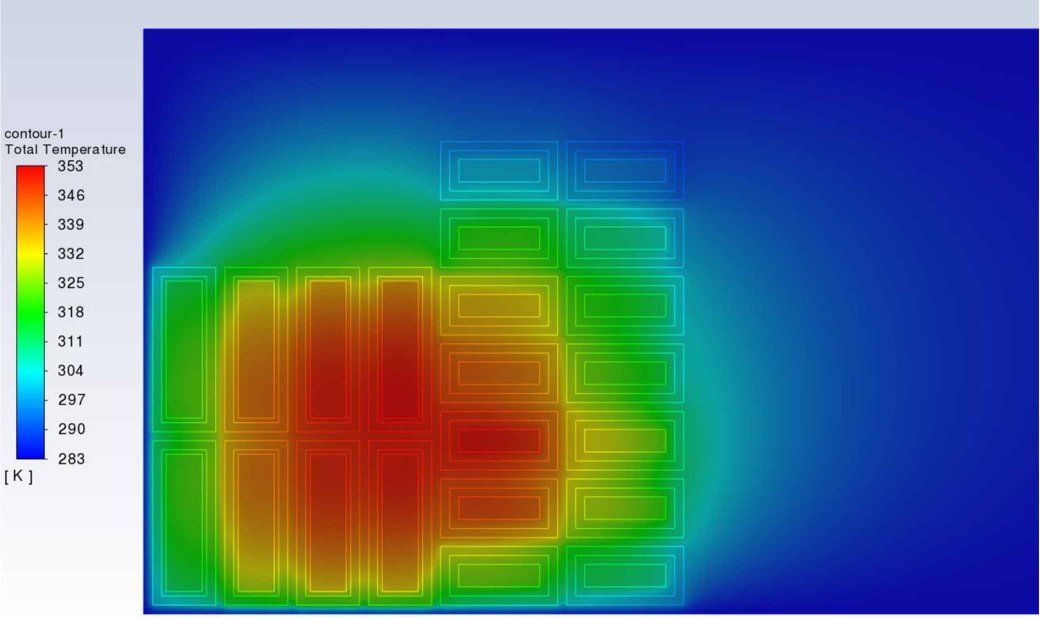

Figure 14. ANSYS Fluent 2D-color contour from the DWH1 after 1 000 days, where the big rectangles represent the shield element packages and the small rectangles represent the dismantled RPVI components.

To validate the results obtained, the simulation was run with a couple of different configurations:

- When the shield element packages were not stacked, the highest temperature was 52 °C. This is the option displayed in the CAD-model in Figure 13.
- When the waste repository was filled with water, the highest temperature was 17 °C.
- A more detailed 3D-model of the S3-package was also done to ensure correct heat flow from shield elements to the surface of the package, this model corresponded to the 2D-models made.

A more detailed temperature evaluation study was done for used fuel cylinders by Posiva Oy in 2020. As a result, from this study, similar temperatures were achieved, when corresponding thermal power and surrounding conditions were used. (Ikonen 2020)

5.3.6 Schedule

Scheduling of RPV segmentation was done in Microsoft Project Professional and in total the time estimate is 470 workdays, when working with one eight-hour shift per day. The schedule estimation is done based on cutting speed of different segmentation methods and the length of cuts required, earlier work (Kälviäinen, 2018) is used to supplement the transportation and handling estimations. Durations of major work stages are presented on Table 7.

Table 7. Major work stage durations of segmentation of all components decommissioning option.

Work stage	Duration [d]
Shield elements	13.5
Control rods	17
The RPVI	292
Vessel head	30
The RPV	146.88
Total	**468.88**

5.4 Segmentation of reactor internals

The third decommissioning option combines the two previously presented decommissioning options. In this decommissioning option the RPV is decommissioned as in the first option, but instead of disposing it in a silo, it will be hauled to the DWH1 in a horizontal position and no further packaging will be done. The RPVI are segmented as in the second option, the shield elements and control rods are packaged and disposed of as in the second option. This will also eliminate the direct need of the additional containment structure inside the reactor hall, as the segmentation will be done completely under water and aerosol contaminants are thus avoided. The work stages are as in the previous options and the total duration of this decommissioning option is 477 workdays. The estimated schedule is presented in Table 8.

Table 8. Major work stage durations of segmentation of the RPVI decommissioning option.

Work stage	**Duration [d]**
Shield elements	13.5
Control rods	17
The RPVI	292
Vessel head	30
The RPV	124.5
Total	**477**

6 RADIATION DOSES

As per ALARA principle the radiation doses during the decommissioning work should be kept to a minimum whenever reasonably possible. Here carefully made plans can play a vital role, since a well prepared and executed plan will often shorten the time required to complete the work stage and minimize the time personnel is being exposed to radiation.

The radiation doses are calculated based on the dose rates present at the site and the estimated time and number of workers required to complete the work stage. This will produce a collective dose estimation in manSv. The dose rates for the calculation can be acquired from physical measurements from the facility, or as most of the work stages deal with the RPVI, they can be acquired from computer models or calculations. The dose is normally estimated to be only from the gamma-radiation sources, as beta- and alpha- radiation can be effectively prevented with functional radiation protection and good contamination control (Ketolainen, 2008).

Here the collective doses are calculated based on an earlier dose assessment (Ketolainen, 2008) made for Loviisa decommissioning. The activity inventory used in previous assessment is the same as used here, so the dose rates are taken from the previous assessment and supplemented with reports from radiation protection personnel (Pyykönen, 2020), values from Microshield-calculations, and the MCNP-models. The man-hours are also estimations based on the previous assessment, supplemented with the schedule introduced here. The collective dose rates are presented for the major work stages, these stages comprise the handling, transportation and final disposal of the said components.

6.1 No segmentation of components

The majority of the collective dose in the no segmentation of components decommissioning option comes from the handling of the RPV, as the rest of the components can be handled with remote controlled equipment and personnel are not required to go near the components. The dose estimations of major work stages are presented on Table 9. The total collective dose is 0.769 manSv, while in the previous assessment this was 0.857 manSv (Ketolainen, 2008).

Table 9. Dose assessment of no segmentation decommissioning option.

	Man-hours [h]	Weighted average dose rate [mSv/h]	Collective dose [manSv]
RPV	5 285	0.124	0.596
RPVI	1 464	0.027	0.074
Vessel head	1 472	0.003	0.009
Shield elements	1 016	0.024	0.037
Control rods	992	0.016	0.024
Sealing the silo	248	0.167	0.038
Total	**10 477**		**0.769**

The lower dose estimation compared to previous assessment is mainly due to improvement of some RPV handling methods during the transportation. However, dose assessment of the RPVI and closing of the silo is updated making the final collective dose to be nearly the same as before.

6.2 Segmentation of all components

The dose rates for segmentation of the RPVI components are estimated from the reports from handling the RPVI components during the maintenance outages. Since the segmentation of these components will be done in the water-filled reactor pit, this estimation is very conservative. The dose estimations of major work stages are presented in Table 10. The total collective dose for this option is 0.538 manSv.

Table 10. Dose assessment of segmentation decommissioning option.

	Man-hours [h]	Weighted average dose rate [mSv/h]	Collective dose [manSv]
RPV	6 558	0.039	0.338
RPVI	10 944	0.019	0.141
Vessel head	2 272	0.004	0.011
Shield elements	728	0.046	0.033
Control rods	752	0.016	0.014
Total	**21 254**		**0.538**

6.3 Segmentation of reactor internals

The dose assessment for the decommissioning option where the RPVI are segmented and the RPV is disposed of as whole is a combination of the two previous dose assessments, excluding the silo placement of the RPV. The dose estimations of major work stages are presented in Table 11, the total collective dose for this option is 0.698 manSv.

Table 11. Dose assessment of decommissioning option where the RPVI is segmented and the RPV is disposed of as whole.

	Man-hours [h]	**Weighted average dose rate [mSv/h]**	**Collective dose [manSv]**
RPV	4 733	0.119	0.484
RPVI	10 944	0.019	0.141
Vessel head	1 640	0.035	0.025
Shield elements	728	0.046	0.033
Control rods	992	0.016	0.024
Total	**18 797**		**0.698**

6.4 MCNP-models

MCNP-models were made to support the dose assessment and practicality of some chosen decommissioning methods. As the making of MCNP-models is relatively time consuming, only a few of the models required for the whole decommissioning process of the RPV were performed. Additional models should be utilized for the total dose assessment of the RPV decommissioning, as the resulting color contours are a useful way of representing the radiation cones present during the work stages.

While most of the uncertainties concerning the MCNP-simulation are dependent on the accuracy of the input data, the simulations also contain a level of uncertainty based on the statistical method of calculation which depends on available simulation resources and time. Since this uncertainty is directly related to the statistical accuracy, MCNP-simulations also produce a percentual value for this uncertainty. When this uncertainty percentage of the MCNP-results is below 10 %, the results can be considered accurate (Shultis, 2011).

6.4.1 Segmentation of RPV in the reactor pit

A dose rate color contour of the RPV situated in the reactor pit before being segmented is presented in Figure 15. Two different scenarios were calculated, one with two m high and 0.5 m thick radiation shielding wall included and one where the wall was not included. As seen from the figure, strongest radiation cone is directed upwards from the reactor pit and the dose rate on the floor level stays considerably low, which allows short term tasks to be done on the +25.40 level. However, the possibility of the situation changing can already be seen from the figure, as strong radiation cones can be seen shooting from the nozzle openings of the RPV. This would indicate that the top part of the RPV blocks some radiation and when the top flange is cut off, the radiation cones might spread on a wider area of the floor level and on the surrounding walls. For this reason, an estimation of dose rate change should be done separately for every work stage.

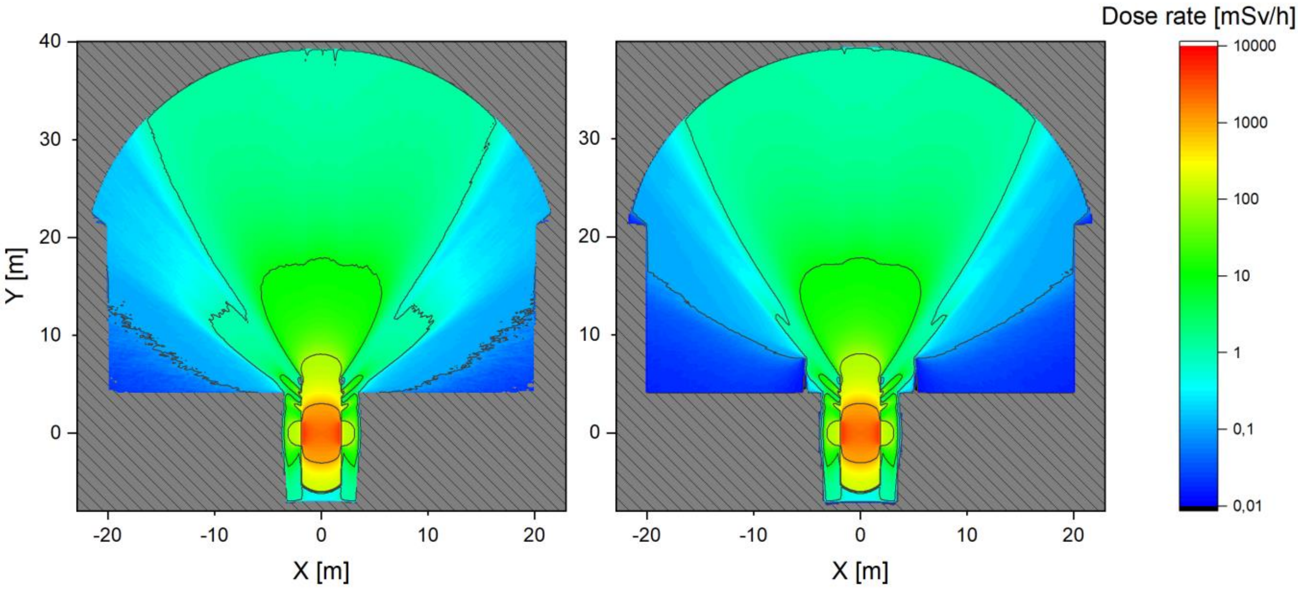

Figure 15. The color contour of MCNP-model of the RPV while it is in the reactor pit. Picture on the right has the radiation shield wall included. Values with higher than 10 % uncertainty have been removed from the results.

The segmentation plan includes a radiation protection wall to be built around the reactor pit opening, to cover the lifting of segmented parts to their packages. By extending this wall around the reactor pit, the dose rates from the RPV can be significantly reduced. From the comparison of the radiation dose color contours, the dose rate at two meters from the reactor pit can be seen lowered from ~0.2 mSv/h to ~0.04 mSv/h all around the floor level. While this reduction is considerable, the radiation scattering from the ceiling of the containment prevents long term stay in the reactor hall and will probably prevent any other work to be done inside the reactor hall, while the RPV is being segmented.

6.4.2 Shield element package

Figure 16 presents two different dose rate contours for the S3-disposal package, with package wall thicknesses of 100 and 200 mm. In the simulation, the total activity of 40 shield elements (1.54E+16 Bq) is assumed to be spread out evenly between the elements. The fact that dose rates could be lowered by placing new elements with higher activity to the middle and use the older elements as additional shielding is not modelled, as no activity inventory assessing the activity of differently aged elements exist yet.

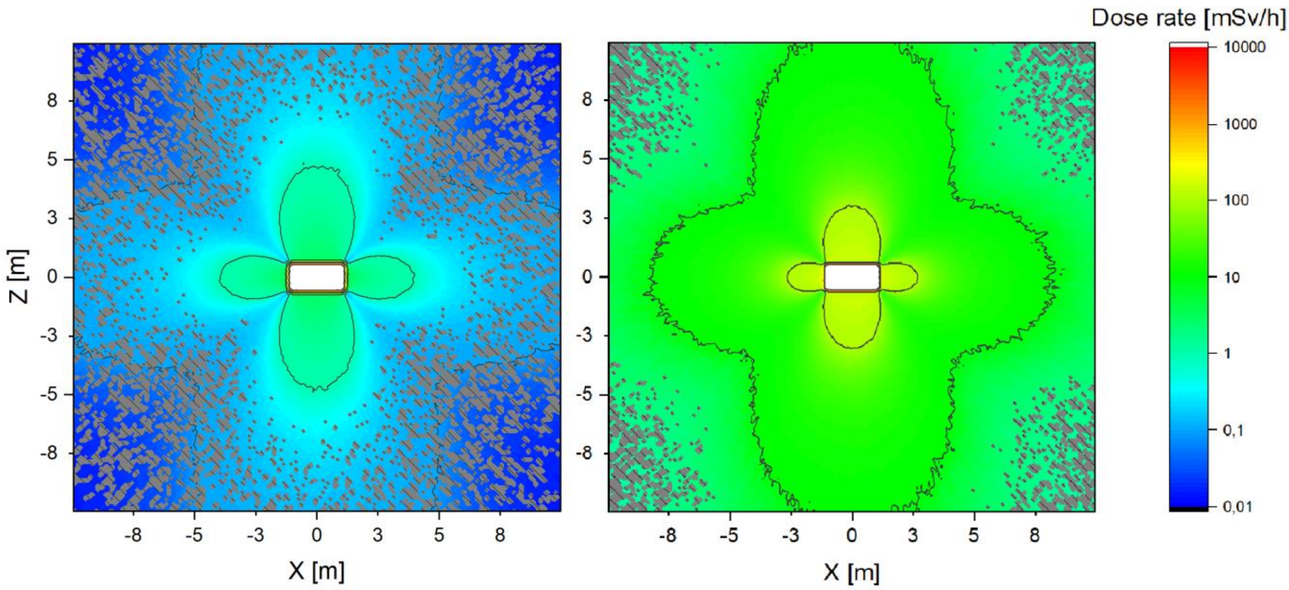

Figure 16. Top-down color contours of MCNP-models where the S3-disposal package is loaded with 40 shield elements, projection taken from the middle height of the package. Image on the left has a wall thickness of 200 mm and on the right a wall thickness of 100 mm. The values with uncertainties higher than 10 % have been removed and the max dose rate shown is limited to 10 000 mSv/h.

These results display that the 200 mm wall thickness could be more than required for the safe handling of the package and 100 mm would be too thin without utilization of an additional transport casket. This presentation of the S3-package works as an example of the process how the final waste packages should be designed, as this is an iterative design process where the radioactivity shielding features are balanced against the costs and weight of the package.

6.4.3 Disconnecting the nozzles and plate welding

Figure 17 presents the dose rates in the main circulation nozzle area, before the RPV is disconnected. In the modelled situation the RPV is filled with water to the level of lower main circulation nozzles and a 180 mm thick steel radiation cover is installed on top of the vessel. The source activity in the model is only from the RPV itself, while the activity in the concrete of the biological shield and the heat insulation plates was left out. This was done to simplify the modelling process, when considering the fact that these activities are magnitudes lower than the activity of the RPV.

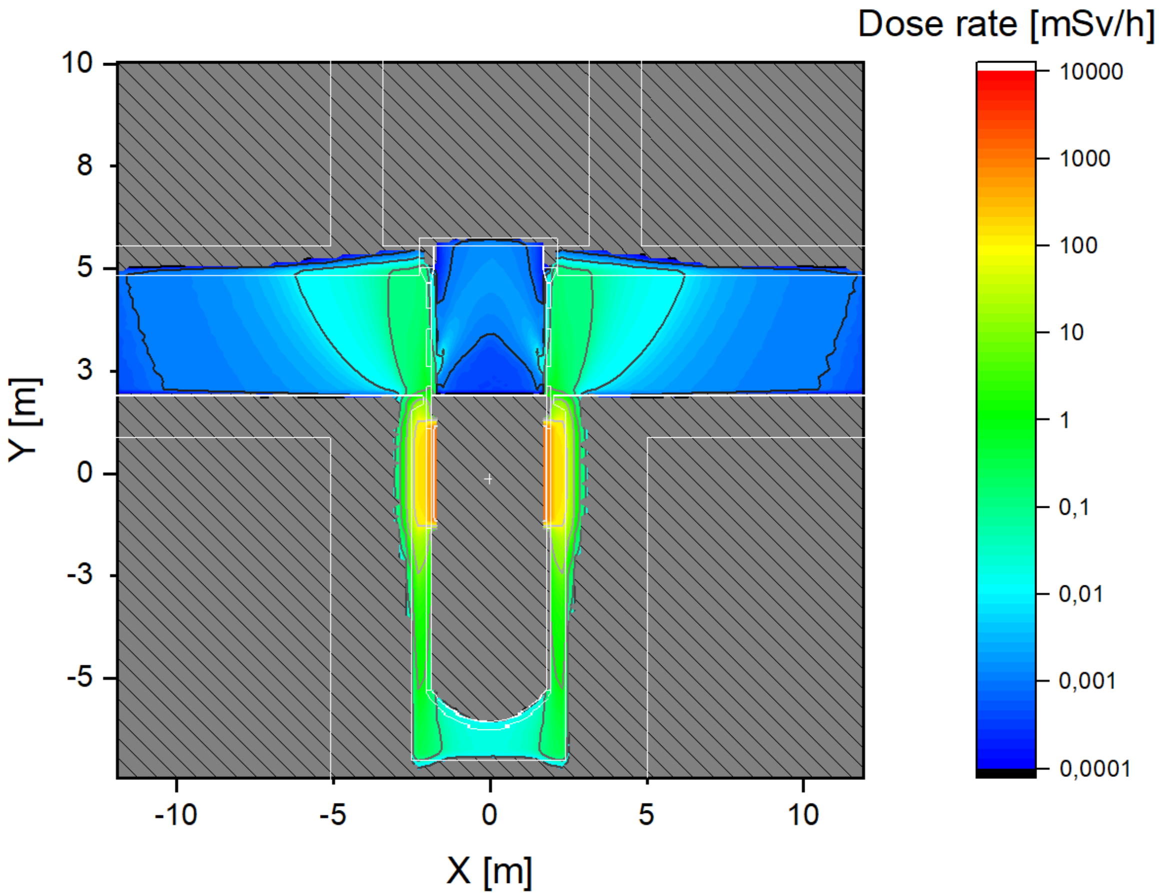

Figure 17. Color contour of the MCNP-model before the RPV is disconnected. Uncertainties over 10 % are removed from to picture.

This model confirms that the radiation dose levels can be kept low enough by filling the RPV with water to allow the cutting of the main circulation nozzles and welding the 20 mm stainless steel plates inside the nozzles, as the dose rate at two meters away from the surface of the RPV is around 60 µSv/h. As seen from the figure there is a >100 µSv/h radiation cone coming from between the flange of the RPV and the concrete support structure. This cone can easily be reduced with temporary lead shielding around the RPV during the work stages. The model is somewhat inaccurate on the part of the RPV flange area and all the features that attach the RPV to the concrete were not modelled. Therefore, this representation can be seen as a conservative estimation. Lead shielding and the structure of the actual flange supports will probably lower the radiation dose levels further in the corridor, as some of the radiation in the corridor originates from the radiation cone scattering from the ceiling of the corridor rather than going through the biological shield.

7 FINANCIAL CONSIDERATION

The decommissioning cost estimation is still a quite unstandardized industry, as the cost estimates are done differently depending on the country, company and even the facility in question. The scope of works for these facilities also vary greatly and sometimes conventional decommissioning may be included in the estimations. While there are already quite many fully decommissioned facilities in existence, most of the decommissioning costs for these facilities are not publicly available and if they are published only the total sum is given or the costs are divided in such a way that the cost of removal of the RPV is hard to estimate. (Lalu, 2020)

Concerning this work, there are few existing cost estimations that can give some direction on the economics of the options presented here. The RPV decommissioning of Oskarshamn NPP in Sweden is estimated to cost 26 – 40 M€ in 2018 price level per reactor unit and the RPVs in Forsmark would cost 39 M€ respectively (Lalu,2020). These units however have an output of almost two times larger than Loviisa and they are boiling water reactors, in which the reactor is generally more complicated and consequently comes with higher costs to decommission than pressurized water reactors.

As discussed in chapter 2, the Trojan NPP in the United States is the only commercial reactor where the RPV has been removed without segmentation. As United States is one of the industry leads in nuclear decommissioning, there is also more publicly available information about actual costs of decommissioning projects. Table 12 presents a comparison of the estimated and actual costs of decommissioning of some NPPs in the United States.

Table 12. Costs of decommissioning from United Sates (Lalu, 2020).

Facility	Cost estimate M€ 2018	Actual cost M€ 2018
Haddam Neck	383.8	851.6
Maine Yankee	416.1	533.0
Trojan NPP	344.1	300.1

This comparison displays that only the Trojan NPP was able to undercut the estimated costs. There are however multiple reasons for these differences; the Trojan NPP had somewhat higher release constraints for the radioactive waste, so in comparison some nonactivated material had to be processed in Haddam Neck and Maine Yankee; Haddam Neck was planned to be decommissioned by an external contractor, but during the project a decision of using an internal organization was done, which caused delays and administrative problems. Maine Yankee also had similar problems, but not in the same scale. This also displays how complicated the process of nuclear decommissioning is and how local regulation can affect the costs.

The cost estimates between the disposal options presented in this thesis are based on an earlier report (Kälviäinen & Kaisanlahti, 2018). The work methods presented in the earlier report differ somewhat from the methods presented in this thesis, but the overall cost estimates remain in the same range. Exact cost estimates made cannot be presented in this thesis, but the option where all the components are segmented costs around twice as much as the option where the components are disposed of without segmentation. If the RPV is not segmented, the overall cost stays between the other two options.

8 LONG-TERM SAFETY

This chapter will go through the results of long-term safety assessment for the disposal concepts presented, while the comparison and discussion between these results is then addressed in chapter 9.5.

The long-term safety of disposing radioactive materials is assessed with a safety case, which is a set of reports studying different factors affecting the safety of final disposal of radioactive materials. The purpose of a safety case is to illustrate the consistence of a disposal concept to the regulatory requirements concerning the long-term safety, in terms of how the radioactivity is released from the waste and transported to the biosphere via groundwater flow and gas formation. This is achieved by combining observed behavior of materials of release barriers, environmental conditions and effects to mathematical models, that demonstrate the estimated future behavior of these factors. In nuclear industry the expression long-term literally is a long time in comparison to the history of modern civilization of a mere 12 000 years, as in disposal of nuclear waste to the Loviisa LILW repository the assessment period in the safety case is hundred thousand years.

Since the decay time of some radionuclides like Cl-36 ($T_{½}$ = 300 000 a) is so long, total prevention of radioactivity release to the biosphere would be incredibly expensive and hard to achieve, as all materials and release barrier will corrode over time. None of the long-term storage methods widely used by other industries are designed to last for centuries let alone millenniums, so in most cases nuclear industry has to design their own disposal packages and other storage systems. The design basis of a nuclear waste repository is to introduce multiple different release barriers, that hinder the release and transportation of radionuclides until they have had time to decay down to safe activity levels.

This multi-barrier principle consists of different structural and chemical solutions that enclose the radioactive wastes, so that the barriers support the radionuclide release hindering features of each other as long as possible. These barriers consist of waste packages, concrete structures and the bedrock the waste repository is excavated to. Depending on the activity levels, the waste packages may be made of sheet metals, concrete or thick steel. The steel containers are able to withhold the radionuclides inside them until their integrity is lost, while concrete will diffuse some radionuclides trough it over time. The concrete structures of the waste repository have two functions, firstly they decelerate the flow of groundwater in the waste repository and offer structural protection for the waste packages, secondly the concrete keeps the conditions alkaline which reduces the corrosion speed of the steel alloys and thirdly it also absorbs some of the radionuclides released from the waste. The Finnish bedrock itself offers a stable and well protected environment, where the conditions can be expected to remain considerably unchanged for the future millennia. The dense bedrock also effectively limits the flow of the groundwater to fracture zones hindering the transportation of radionuclides to the surface environment.

In the safety case modelling process, different scenarios are formulated to represent the waste repository system and evolution of the disposal system based on natural and manmade changes. In radioactive waste disposal, the scenarios are created by identifying boundaries of the scenario based on the regulatory specifications and key factors affecting the performance of the release barriers. The key factors e.g., the groundwater flow through the waste repository, evolution of concrete release barriers and wall thicknesses of disposal packages, are analyzed and the fulfilment of a performance target is set as the reference evolution, i.e., in the reference state everything works as designed. The key factors can have different values depending on the factors affecting the release barrier performance, e.g., the corrosion rate of the metal disposal packages would depend on microbial corrosion, early loss of alkaline conditions and possible defective welds. While the number of different scenarios formulated this way increase exponentially due to the excessive number of different combinations of variables to be considered, the scenario formulation process reduces the number of plausible scenarios to a few distinctive ones. (Nummi, 2019a)

This assessment of the long-term safety of the three RPV disposal concepts is based on the safety case made for Loviisa LILW repository (Nummi, 2019a). Exact scenario boundaries and key factor definitions used in this assessment can be found from the safety case. The simulations of the RPV disposal scenarios were performed using Ecolego software (Mäki, 2021) and modified radionuclide release and transport models are based on the Loviisa LILW repository safety case. As the Loviisa safety case assesses the safety of all waste generated during the operation and decommissioning of both Loviisa reactor units, the RPV release rates were not separable from the results. Therefore, new simulations were made so that the differences between the concepts could be assessed.

The design details of the waste disposal packages are presented in chapters 5.2.1 and 5.3.3.

8.1 Loviisa LILW repository

The Loviisa LILW repository is excavated into the rapakivi granite bedrock 110 meters below the facility, the layout of the waste repository is presented in Figure 18. While the disposal site is considered very stable and the bedrock is relatively dense, there are still some fracture zones present that allow groundwater flow to some parts of the waste repository. Currently the maintenance and the solidified waste halls are ready and in operation, together with the access tunnel, and personnel and ventilation shafts. The DWH1 and the RPV silos where the components would be disposed of, are already planned but are not yet excavated. The placement of the RPV silos has already been changed once, as the old location was estimated to intersect additional existing fracture zones. (Nummi, 2019a)

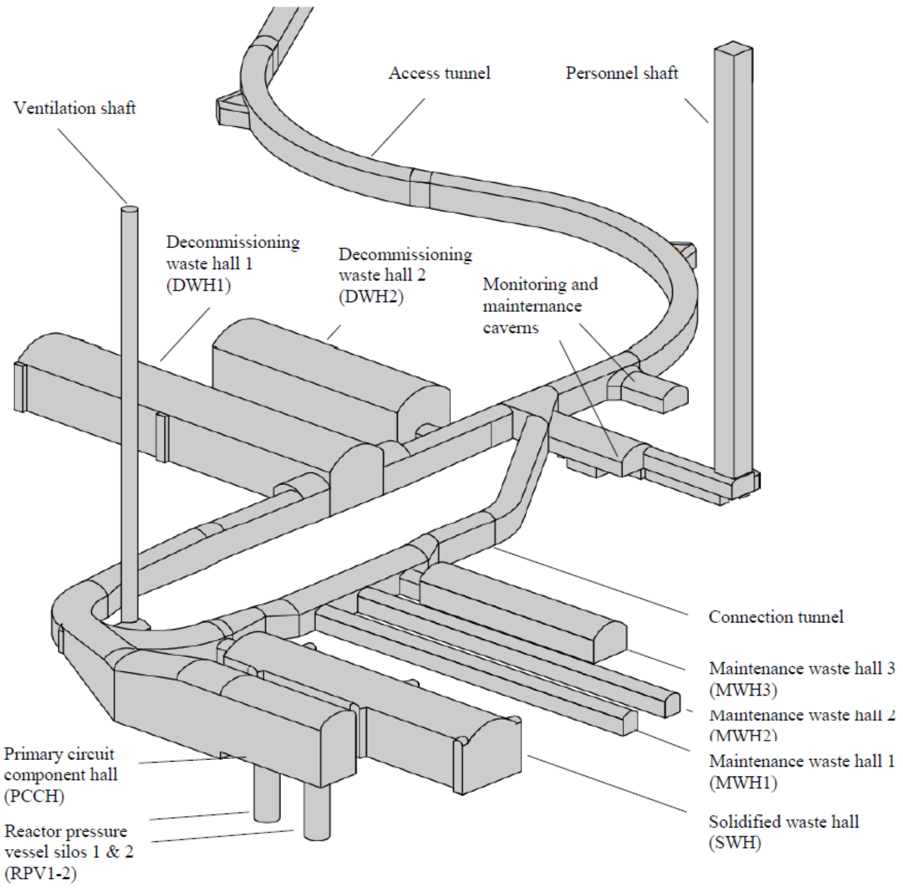

Figure 18. Loviisa LILW repository layout (Nummi, 2019a).

8.2 Analysis of dose release

The choice between the different disposal concepts to be modelled was done based on the scenarios presented on the safety case of Loviisa LILW repository, as the performance assessment and formulation of the scenarios (Nummi, 2019b) was readily available, and the results acquired here would be easily comparable to the safety case. The scenarios modelled were base scenario, variant scenario with accelerated concrete degradation and variant scenario with initial defect in welds. The disturbance scenario presented in the safety case with a large earthquake was left out, as it was estimated that it would not present any comparable results between the RPV disposal options, as it would have the same effect on all of the disposal options. These scenarios were then solved with a deterministic as well as a probabilistic approach, to take the variable key factors and the uncertainty of parameter selection into account.

- The *base scenario* works as a reference for the disposal concept, assuming that all the release barriers last as long as designed, the waste packages will not lose their integrity prematurely and that the concrete degrades as presumed.
- The *accelerated concrete degradation* variant scenario assumes that the concrete release barriers do not retain their structural integrity, nor their chemical abilities on limiting the radionuclide transport. Accelerated degradation also affects the corrosion rate of metals as the alkaline conditions are lost earlier, and together with the microbiological corrosion cause preliminary loss of integrity of the waste packages.
- The *initial weld defect* variant scenario assumes that the welds of the RPV or some of the packages contain a defective weld, which will allow the groundwater to fill the container. This will lead to corrosion process initiating simultaneously from both sides of the container walls and on the radioactive waste inside them. Which will release some radionuclides that are slowly transported out of the container through the weld defect and causing a burst of activity being released when the groundwater flow is increased temporarily after a glacial period ends. Together with microbiological corrosion this may also cause preliminary loss of integrity of the waste containers. (Nummi, 2019b)

While the probability of an initial weld defect with modern welding and inspection methods can be estimated to be very low, it cannot be completely ruled out. In the RPV disposal option the defect is assumed to be located on one of the nozzle plates of the RPV and on the segmentation disposal option the defect is assumed to be on one of the S3-containers with the shield elements.

The results of the simulations are presented as summed normalized release rates, so that "*the sum of the ratios between the nuclide-specific activity releases and the respective constraints shall be less than one.*" (STUK, 2018). This sum of the ratios is solved from

$$S(t) = \sum_n \frac{R_n(t)}{RC_n} \tag{8}$$

where $R_n(t)$ [Bq/a] is the nuclide specific (n) activity release rate from the waste repository to the surface and RC_n [Bq/a] is the release constraint of the nuclide (Table 13). As regulations allow a moving average of the results to be calculated, this has been done over the allowed 100-year period. (Jansson, et. al., 2019)

Table 13. Constraints of specific nuclide releases into surface environment (STUK, 2018).

Radionuclide	Release constraint [GBq/a]
Long-lived alpha-emitting curium, radium, americium, thorium and protactinium isotopes.	0.03
Se-79, Nb-94, I-129 and Np-237	0.1
C-14, Cl-36, Cs-135 and long-lived uranium isotopes	0.3
Sn-126	1
Tc-99 and Mo-93[5]	3
Zr-93	10
Ni-59	30
Pd-107	100

These release constraints are applied to the period ranging from 10 000 to 100 000 years, so the results of the simulations are also presented on the same time span. In the Loviisa safety case (Nummi, 2019a) the dose assessment period between waste repository closure and 10 000 years did not indicate that any remarkable dose release would happen in these scenarios, consequently a choice of not solving them for this thesis was done. Except when the RPV is disposed of without sealing plates, as the release of radionuclides was expected begin right after the waste repository is filled with water. The end of the assessment period was chosen based on the inventory of radionuclides present and their respective decay times.

[5] No value given in YVL D.5, STUK recommendation is to use the same value as for Tc-99 (Jansson et. al., 2019).

The activities used for the safety case calculations were from the activity inventory (Appendix 1), but decay time to the estimated closure of the waste repository at 2068 (Nummi, 2019a) was applied to the inventory using equation (7). So, the activity of short-lived nuclides such as Co-60 has already halved multiple times and nuclides with decay time less than five years were excluded altogether. However, when considering the decay time of the radionuclides in the disposed of components and the used assessment period, the short-lived nuclides would probably have little effect on the release rate results.

8.2.1 Deterministic approach

The deterministic results of the base scenario and two variant scenarios from the disposal option where the RPV works as a disposal package are presented in Figure 19. The results indicate that the corrosion of the outer shell of the RPV begins to release the radionuclides to the groundwater before the beginning of the assessment period of 10 000 years, from which they are transported to the surface environment.

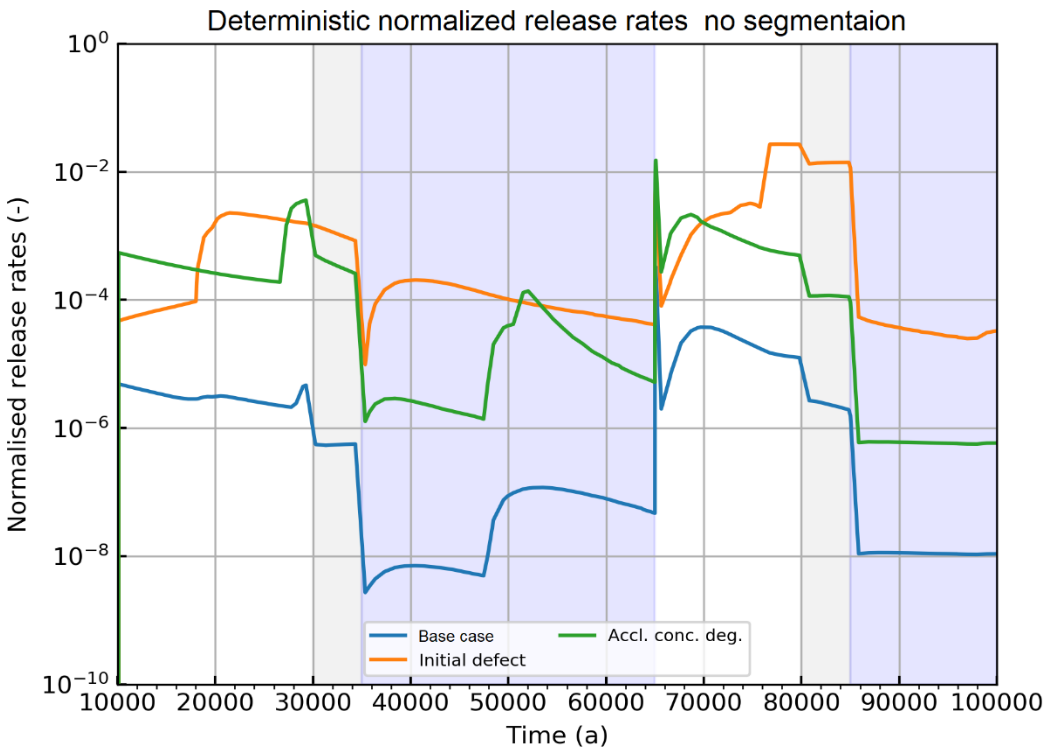

Figure 19. The deterministic summed normalized release rates of the option where the RPV works as a disposal package. The grey background denotes a permafrost and the violet a glacial period.

However, as the activity of the outer shell is low, the summed normalized release rates stay well below the constraints in all scenarios, even though a spike of released activity can be seen when the glacier retreats after the first glacial period. The highest summed normalized release rate can be seen in the initial weld defect scenario, as some of the activity in the RPVI is also released. The defect is however estimated to be so small, and the concrete filling will hinder the transport of radionuclides, so that no significant release will happen before the first glacial period ends. After the glacial period is over, the only remaining radionuclide with considerable activity is Ni-59, which alone is not enough to exceed the release constraints. In the two other scenarios the RPV stays intact and the activity is released solely from the RPV shell. (Jansson et. al., 2019)

The deterministic results of the initial defect variant scenario from the segmented disposal option is presented in Figure 20. The most notable difference in the segmented disposal option is that the base scenario and accelerated concrete degradation scenarios do not give any activity release during the 100 000-year assessment period, therefore they are absent from the graph.

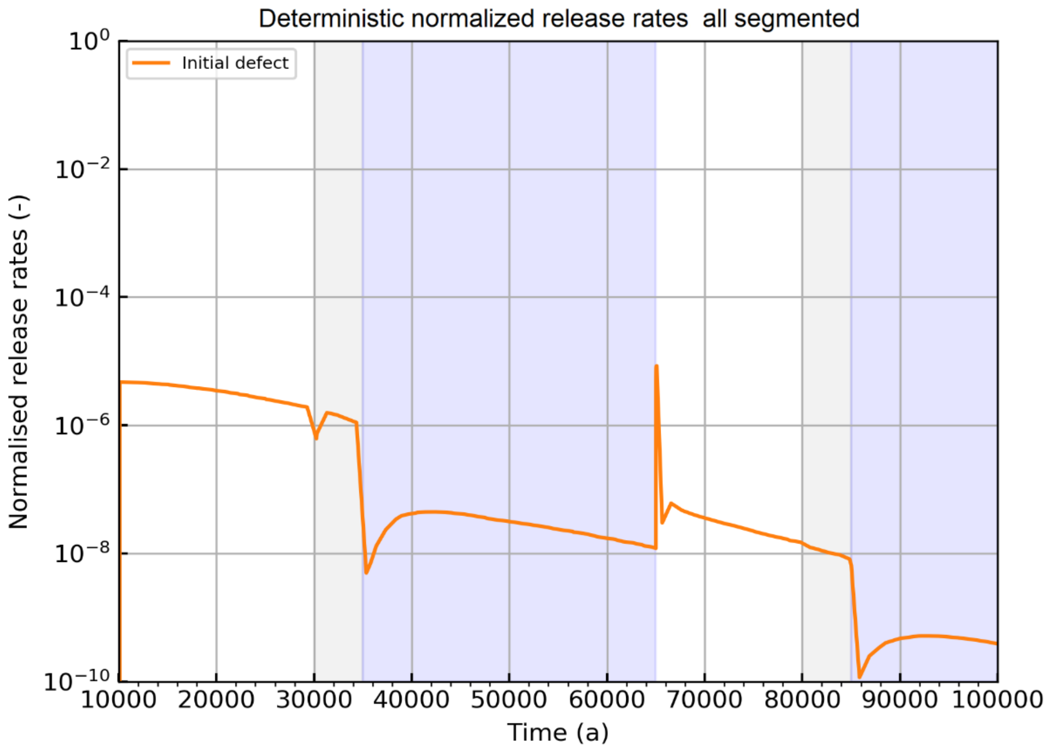

Figure 20. The results from deterministic summed normalized release rates of the segmented disposal option. The grey background denotes a permafrost and the violet a glacial period.

The summed normalized release rate of the initial weld defect scenario can be seen to be orders of magnitude lower than from the RPV, as the weld defect is only assumed to affect one of the S3-containers.

8.2.2 Probabilistic approach

In addition to the deterministic analysis, the regulations state that the uncertainties and sensitivities concerning the simulation parameters shall be assessed (STUK, 2018). Here this assessment is done by making probabilistic analyses of the scenarios. The statistical analysis used in the Loviisa safety case utilizes Latin Hypercube Sampling method to ensure the randomization of simulation parameter values from their probability distributions. The different scenarios with varied simulation parameter values are solved multiple times to form probability distributions of the results, from which the uncertainties and sensitivity of the results can be assessed. However, only the uncertainties of the segmented disposal option are assessed here, as the uncertainties of the other disposal option are presented in the safety case of Loviisa. The number of realisations used for the RPV disposal package option and for the segmentation option was 200 and 1 000 realisations respectively. The lower number of realisations for the first option was chosen due to limitations on available computational resources and due to the fact that the results could be confirmed from the Loviisa safety case. To assess the results conservatively, the 95th percentile of the obtained results is compared against the release constraints. (Jansson et. al., 2019)

Due to the way modelling uncertainty multipliers function, the parameters can sometimes reach considerably high values and produce realisations where parameters such as corrosion rate reach values that cause the packages to lose their integrity rapidly. For this reason, the histograms presented display realisations that exceed the release constraints, that are not present in the graphs. This is a sum of multiple unlikely factors to take effect at same time, which in reality is highly unlikely to occur. However, when the number of such realisations grows high enough, they are displayed in the graphs and are more likely to actually occur.

Base scenario

The probabilistic results of the base scenario of the disposal options option where the RPV works as a disposal package are presented in Figure 21. When the components are segmented, the summed normalized release rate is nonexistent, and it is not displayed on the graph. Same as in the deterministic results, the probabilistic results for the base scenario indicate that the release constraints would not be exceeded on either of the disposal options.

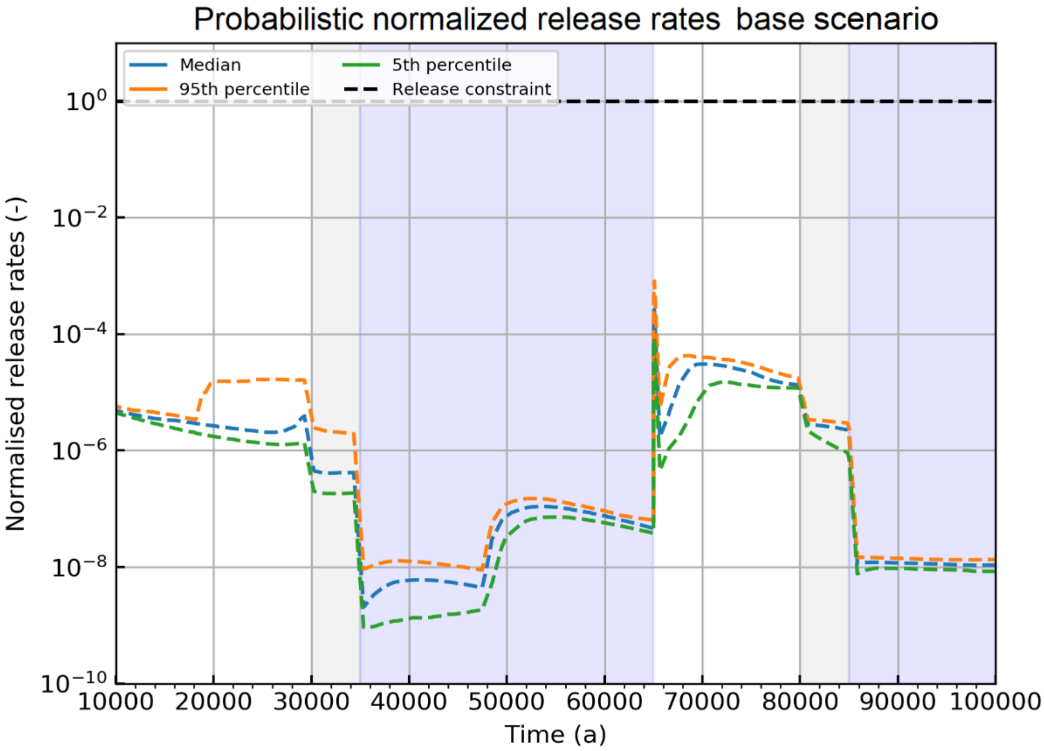

Figure 21. The probabilistic summed normalized release rates of the base scenario. The disposal option where the RPV functions as a disposal package is presented with a dashed line, while the segmented option is presented with a solid line (not visible in the figure). The grey backgound denotes a permafrost and the violet a glacial period.

Again, the activity release from the disposal option where the RPV works as a disposal package is only from the shell of the RPV and varying the key factors has only little effect when comparing these to the deterministic results. In the segmentation option, the waste packages do not lose their integrity in the majority of the realisations during the 100 000-year assessment period and consequently there is no release of activity displayed in these scenarios.

Even though in some realisations the packages of the segmented components fail causing the activity to be released, only one of the 1 000 realisations exceeds the release constraints as seen in Figure 22.

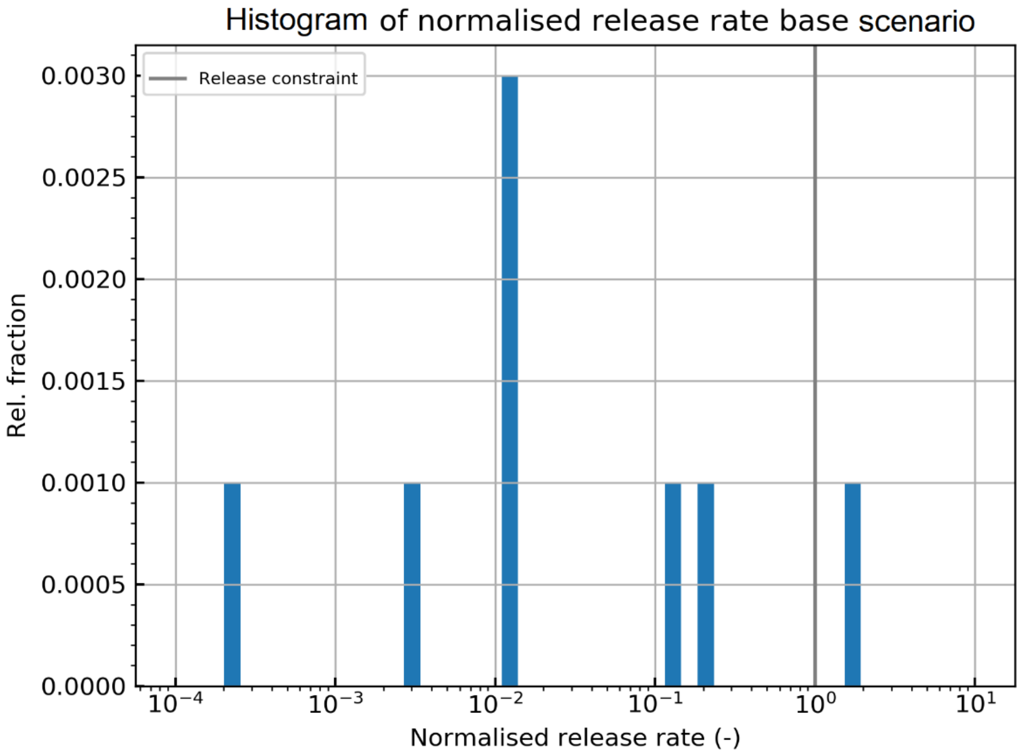

Figure 22. A histogram displaying the summed normalized release rates of the base scenario for the segmentation disposal option.

Initial weld defect

The probabilistic results of the initial weld defect scenario from both of the disposal options are presented in Figure 23. The probabilistic results from the initial weld defect scenario show more distinctive differences to the deterministic results.

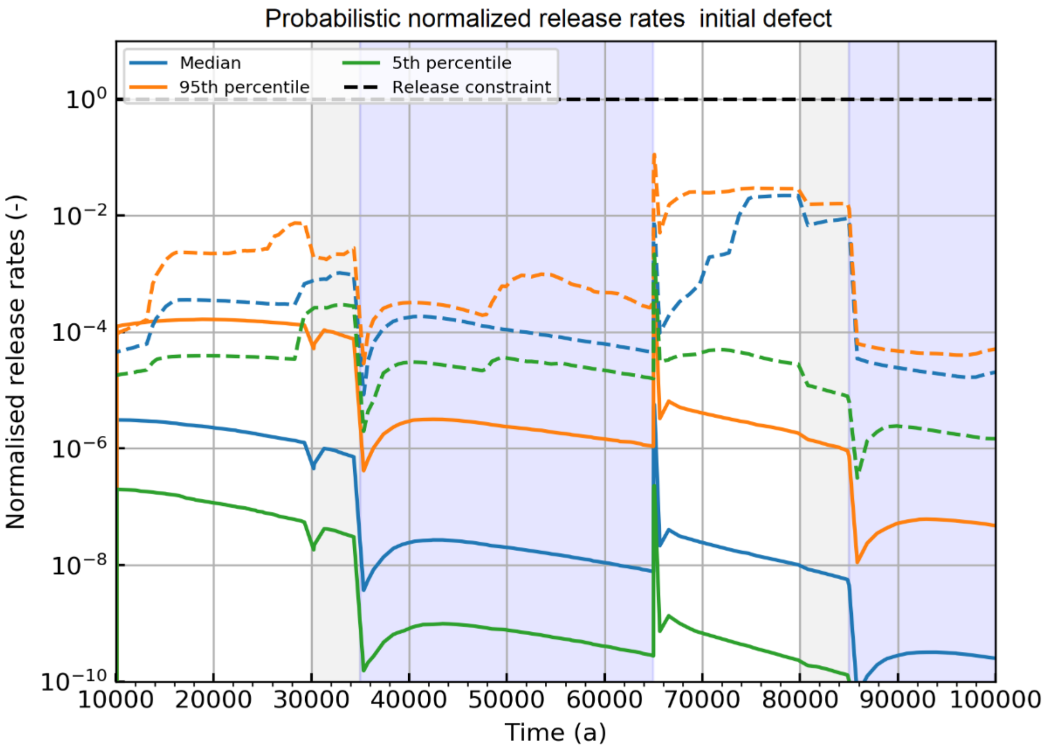

Figure 23. The probabilistic summed normalized release rates of the initial weld defect scenario. The disposal option where the RPV functions as a disposal package is presented with a dashed line, while the segmented option is presented with a solid line. The grey backgound denotes a permafrost and the violet a glacial period.

The difference can be seen especially for the segmentation disposal option where the difference between the 5th and the 95th percentile is relatively large. In the histogram the 95th percentile of the maximum of the summed normalized release rates is 0.001 and one of the realisations can be seen to go over the release constraints, which would indicated that an initial defect in welds could lead to an activity release exceeding the regulations, if the defect would be greater (Figure 24). The same results can be observed in the maximum of the summed normalized release rates of the Loviisa LILW safety case in the RPV disposal option, but with the 95th percentile of the summed normalized release rates being 0.53 (Nummi, 2019a). One way to diminish the release rate spikes would be to add crushed concrete as filling into the waste repository, this would keep the conditions alkaline for a longer time and slow down the corrosion rate. (Jansson et. al., 2019)

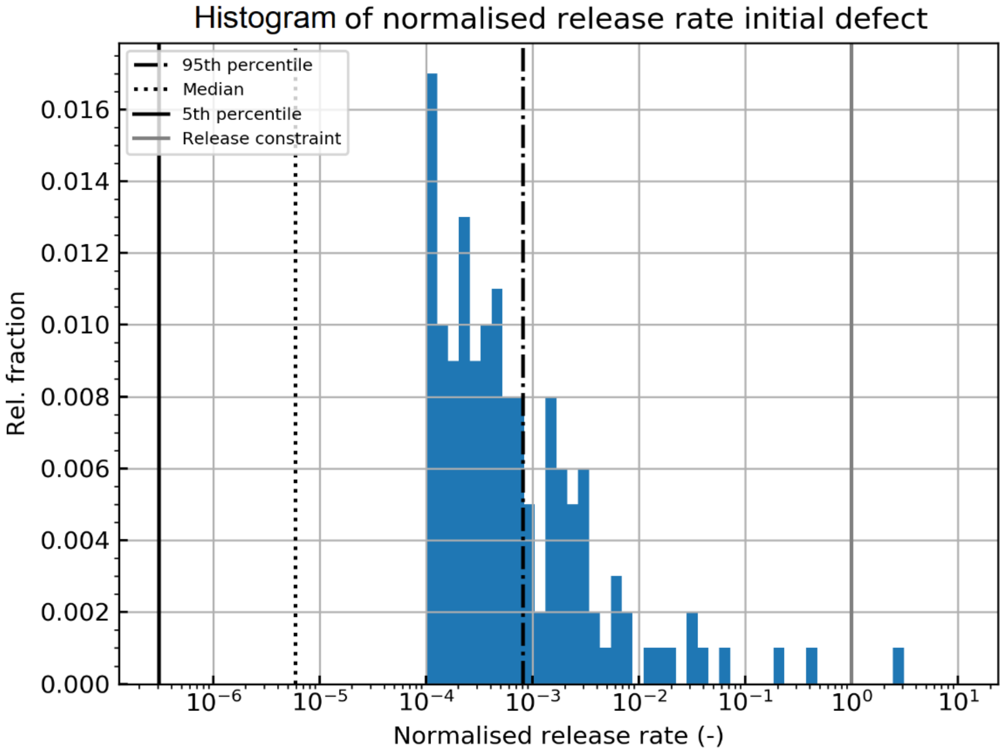

Figure 24. A histogram displaying the summed normalized release rates of the initial weld defect scenario for the segmentation disposal option.

Accelerated concrete degradation

The probabilistic results of the accelerated concrete degradation scenario from both of the disposal options are presented in Figure 25. These results show even more distinctive difference to the deterministic results.

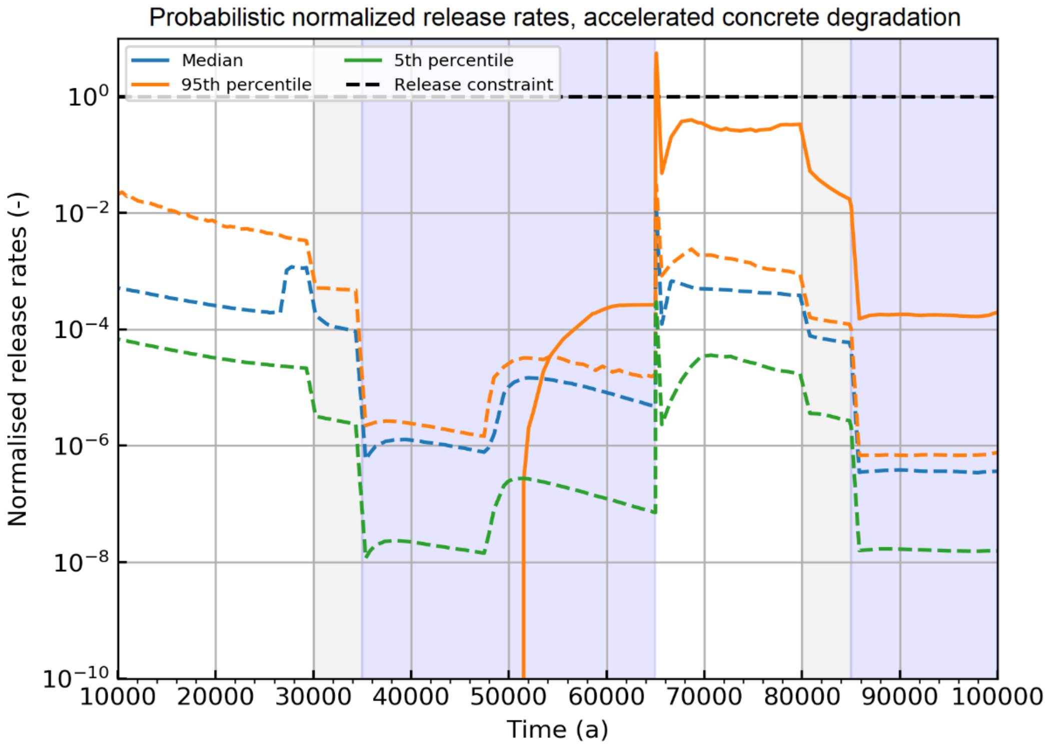

Figure 25. The probabilistic summed normalized release rates of the accelerated concrete degradation scenario. The disposal option where the RPV functions as a disposal package is presented with a dashed line, while the segmented option is presented with a solid line. The grey backgound denotes a permafrost and the violet a glacial period.

The difference is again seen especially in the segmentation disposal option where the lines for 5th percentile and median are not drawn to the graph, as the integrity of the containers is not lost, and the release rates stay at zero during the observation period. The 95th percentile however can be observed to exceed the release constraints after the first glacial period ends. This high activity release in this disposal option is caused by increased groundwater flow due to failed concrete plugs of the waste repository, together with loss of alkaline conditions which cause increased corrosion rates leading to loss of integrity of waste packages. Due to the highly conservative key factor and parameter assumptions and consideration of the fact that the area is unlikely to be inhabited by humans or any large animals at the glacial retreat phase when the site is submerged, this release can be estimated to have only a minor effect on the biosphere.

The 95th percentile release spike exceeding the constraints can be observed to be slightly over five times the release constraint in Figure 26, where a histogram of the maximum of the summed normalized release rates is displayed.

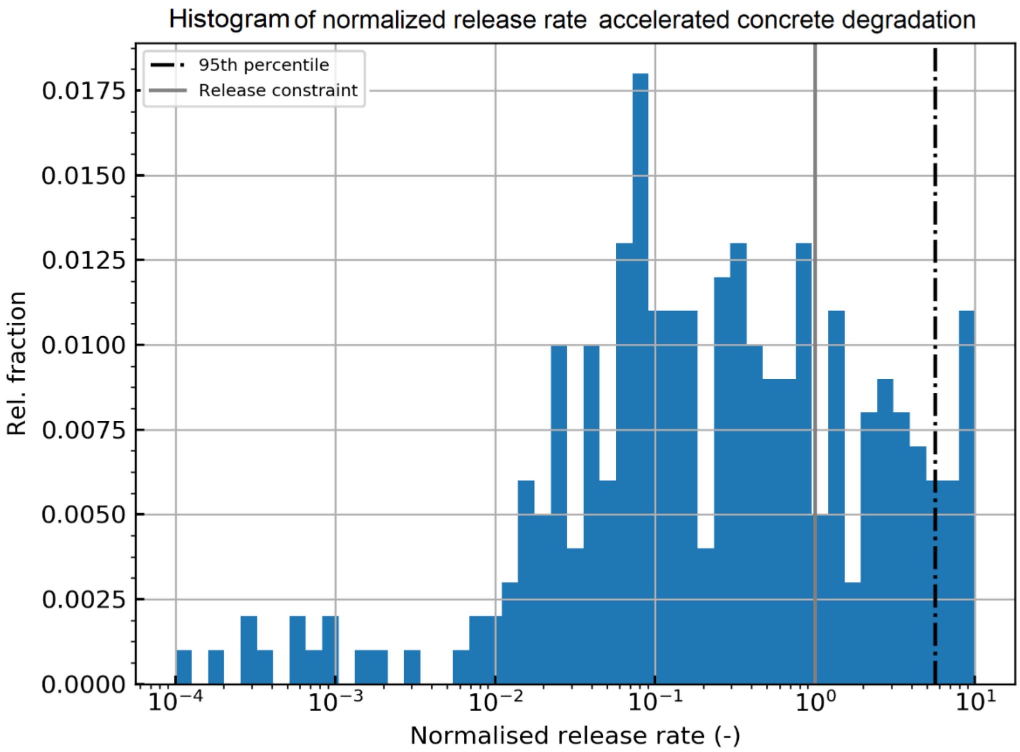

Figure 26. A histogram displaying the summed normalized release rates of accelerated concrete degradation scenario for the segmentation disposal option.

8.2.3 Disposing the RPV without sealing plates

The third disposal option where the RPV is not segmented, but rather disposed of as a whole is modelled only partly. As the segmented RPVI contain over 99.9 % of the total activity disposed of and the components are assumed to be segmented, packed and disposed of outside the RPV in the same way as in the segmentation of all major components option. This would make the results of this disposal option very similar with the segmented option already modelled and difference between them would probably not be even distinguishable. Therefore, instead of modelling the whole scenario, a deterministic simulation containing just the RPV without the sealing plates was made. To further simplify the simulation only releases from one of the RPVs was simulated and these results were multiplied by two. The effect of this solution is estimated to be only that the actual release rate of nuclides such as Ni-59 would be somewhat lower than simulated, as larger amount of Ni-59 would probably lead to precipitation at some scale. The deterministic results for the RPV being disposed of without the plates is presented in Figure 27.

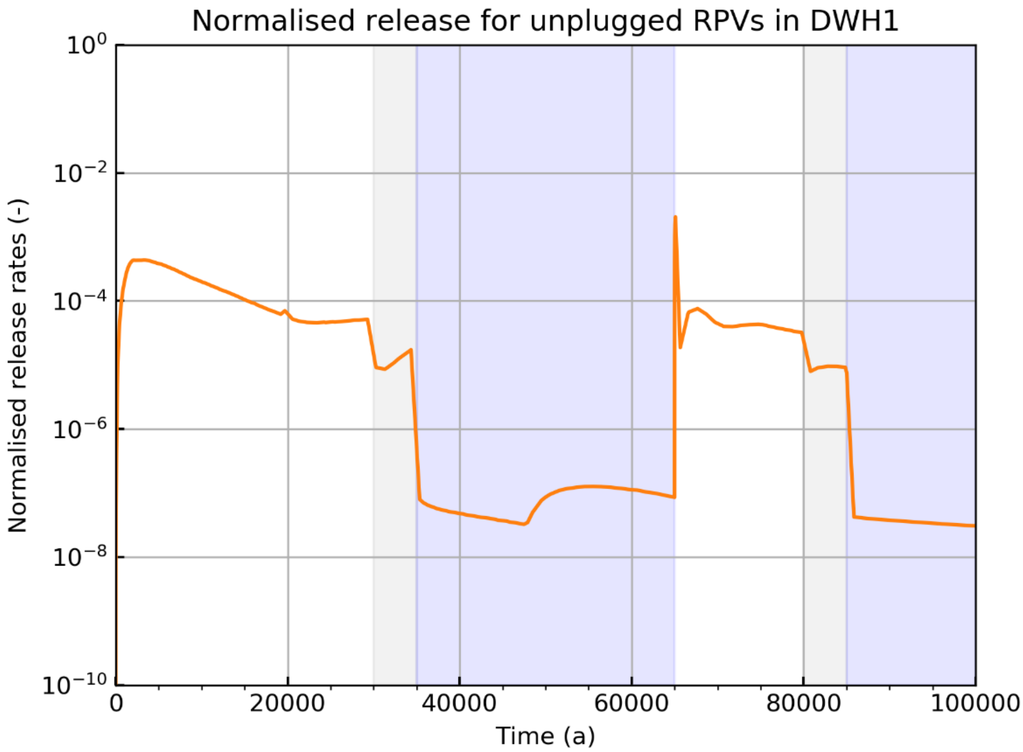

Figure 27. The deterministic summed normalized release rate model for unsealed RPVs.

In this simulation the welded stainless steel plates designed for the RPV in the first disposal option were left out, allowing the groundwater to fill the RPV right after the closure of the waste repository. The vessel head of the RPV is however bolted on its place and limits the flow to and from the RPV to an area of 3.4 m^2 instead of the 11.51 m^2 in case the vessel head would be left out. Otherwise, the key factor and parameter assumptions are as in the base scenario. However, the observed time period starts from the closure of the waste repository instead of 10 000 years after it.

From the results the activity can be seen to begin separating from inner and outer shells of the disposed of RPV right after the closure of the waste repository. However, the amount of activity released is not too high when comparing it to the regulatory constraints, even while it is orders of magnitude higher than for the sealed RPV.

9 COMPARISON

In this chapter the decommissioning option alternatives are compared by the results presented in earlier chapters, and a couple of matters that were assessed during the planning process.

9.1 Decommissioning process

On an overall scale the segmenting of the components will be somewhat of a more complex process and will require more detailed planning and equipment than removing the components as whole. Segmentation will also cause somewhat more disruptions in the reactor hall, as the reactor hall will need to be evacuated when the highly active segments are lifted from the reactor pit. The amount of total waste generated will also be higher as some of the equipment used in the segmentation will need to be disposed of as LILW and the water used during the segmentation process will end up as liquid waste that needs to be processed. When comparing the size of the packages, the disposed of components will also require at least two times more space from the repository when segmented and packed.

The risk of the different decommissioning options can be roughly derived from the complexity and number of work tasks done during the decommissioning. When the RPV is removed as a whole there are fewer work stages to be completed, but the stages are more challenging and the risks are considerably higher e.g., the lifting or transport equipment failure during the transportation of the RPV would be much more challenging to repair than the same happening while a single disposal package is transported. Nonetheless preparation of every work stage should include detailed preplanning and a mockup phase where the tools and systems are tested in nonradioactive conditions.

9.2 Schedule

The durations following the critical path of different work stages for the three decommissioning options are presented in Table 14. These schedules are only made based on the work stages needed for the RPV and the RPVI decommissioning, while the decommissioning processes of the rest of the facility are disregarded.

Table 14. Decommissioning option durations.

Decommissioning option	Duration [d]	Duration [a]
No segmentation of components	255.75	0.98
Segmentation of all components	468.88	1.80
Segmentation of reactor internals	477	1.83

As presented in chapter 5.1 all the decommissioning works are assumed to be commenced after the three-year preparatory phase is completed and an opening to the containment can be made safely. The segmentation option of the RPVI however offers an alternative option to this arrangement, as the segmentation of the RPVI could be done while the nuclear fuel is still cooling down in the refueling pool (Kaisanlahti, 2021). This would leave duration of both of the segmentation options to around 125 days (0.48 a) after the preparatory phase is completed, which would cut the total duration of the facility decommissioning process by up to half a year when comparing it to the no segmentation decommissioning option.

9.3 Finances

The costs of decommissioning of a RPV are challenging to estimate, as the project as a whole contains so many different variables and connections to other areas of the facility decommissioning. The actual work is also scheduled to happen so far in the future, that only a few companies are willing to make tenders for their services. And when the possible continuation of the operation license of Loviisa is considered, the number of interested companies is lowered even further. On a global scale there is also only one commercial NPP where the RPV has been removed without segmentation, this single example would however suggest that removing the RPV as a single piece would be the most economical option, especially when the fact that the RPV would not be transported for long distances is considered.

The previous cost comparison between the decommissioning options (Kälviäinen & Kaisanlahti, 2018) would also suggest that disposing the RPV without segmentation would be the most cost-effective option. The connections to the other areas of the facility's decommissioning could however change these estimations. For example, if also the other large components would be segmented, the overall transportation needs would change. Another major cost factor is the already mentioned effect on the overall duration of the decommissioning project, since this affects the overhead costs of the site. These considerations should however be made on the whole facility level when the decommissioning schedule and methods of the facility components could be considered as a whole.

9.4 Radiation doses

The estimated radiation doses accumulated during the decommissioning work are presented in Table 15. These results would suggest that the segmentation of the components would be the best option when the ALARA principle is followed, as the average dose rate is less than half of the option where no segmentation is done, and the collective dose is the lowest even when the man-hours needed is the highest. This is naturally due to the fact that when the components are segmented, water can be utilized as a radiation shield and when working with the large components this cannot be done.

Table 15. Collective dose rates accumulated during the different decommissioning options.

Decommissioning option	Man-hours [h]	Collective dose [manSv]
No segmentation of components	10 477	0.769
Segmentation of all components	21 254	0.538
Segmentation of reactor internals	18 797	0.698

9.5 Long-term safety

The simulation results for the different disposal options would suggest that all three disposal concepts could be viable options in terms of fulfilling the regulatory constraints. However, the probabilistic analyses displayed that every option had some advantages as well as some disadvantages.

- *No segmentation option*. While not exceeding the release constraints in any scenario, some radionuclides were released in every modelled scenario as the outer shell of the RPV contains some activity. This release however stays way below the release constraints in every scenario. The initial weld defect scenario displayed closest possibility to exceeding the release constraints after the first glacial period was over. This disposal option displayed the least amount of variance between the 5th and 95th percentile of the results and would be considered the safest option when the environmental conditions vary.
- *Segmentation of all components*. This disposal option displayed the safest and riskiest results, as the difference between the 5th and 95th percentile varied most. Most

of the scenarios did not display any activity release at all, while in the 95th percentile of the results there were realisations where the constraints were exceeded.

- *Segmentation of reactor internals*. This option has the disadvantage and advantages of the segmented option as the segmented RPVI contain 99.9 % of the total activity disposed of. While leaving the RPV unsealed might even out the release spike after the glacial period, as part of the activity would already be released earlier. This would be a favorable aspect when inspecting the compliance with regulatory limits, but maybe not so great for the biota during the time before the glacial period. Therefore, sealing the RPV with the stainless steel plates would be a recommended option, even though the constraints are not exceeded.

The RPV was demonstrated to be the most robust disposal package and it is able to withstand most variance in the parameters, without high changes in the release rates. The RPV will however always release some radionuclides, as they are released by the corrosion of the outer shell. While in most scenarios the segmentation option would eliminate the release of radionuclides entirely, but with certain conditions the packages would fail entirely.

Nevertheless, the fact that the disposal packages were simply situated inside the DWH1 to ease up the simulation process by utilizing an existing model should be emphasized. As this placement is not comparable to the well-planned silo placement of the unsegmented RPV, which the activity contained by the disposed of RPVI require. By adding some simple release barriers around the packages of the segmented components, the corrosion rate of the packages could be easily lowered, and the dose releases could probably be totally avoided. In the case of the whole facility's decommissioning plan this has been already done, as most of the disposal packages that will be used will be manufactured from concrete. By adding this feature to the simulated scenarios, the corrosion rate of the packages would be already lowered by a considerable amount.

Even though the initial weld defect would be highly unlikely, all the activity could be released as a result of one such occurrence in the case of the RPV functioning as a disposal package. The segmentation option would somewhat diminish the activity release after such an occurrence, as one defective weld would not affect all the activated components. The length of welds required is however eight times longer, which would mean that the possibility of defective welds occurring would be somewhat higher. The simulations also displayed that a defective weld in one of the S3-packages would be almost enough to exceed the release constraints.

10 PROPOSALS FOR FUTURE

This chapter will list some ideas and proposals for the future decommissioning planning based on the experiences gained from this work.

- Technical documentations. As the Loviisa facility is quite old and it was constructed before CAD-modelling was utilized in planning, the technical drawings of the facility components and structures are sometimes quite hard to locate. These details are however one crucial thing to have if the decommissioning planning is to be done without constant site visits and while visits could be possible, many parts of the facility are inaccessible most of the time or cannot be opened for inspections. For this reason, it could be beneficial to conduct a study on what details are required for decommissioning process planning and where these details can be obtained from.
- Radiation level mapping. Since the MCNP-calculated radiation doses always contain a certain level of uncertainty due to the nature of how the MCNP method works and due to the fact that the activity inventory is also calculated with MCNP, these results could be sometimes confirmed with actual measurements from the facility. For this thesis the radiation levels from the containment building when the RPVI are being lifted from the reactor would have been beneficial, however the process computer of Loviisa averages the past measured values, so the exact measurements are not available for long term. For this reason, it would be beneficial to form a measurement plan for the next long maintenance outage.
- As the long-term safety assessment suggests, the final disposal concept of the segmented components is not finished, as design basis for the disposal packages was mainly based on the safety features concerning radiation protection and the chosen 100 mm weld thickness was just estimated to be more than enough to retain the integrity of the packages. For future considerations it would be beneficial to conduct a study of required minimum wall thickness of waste disposal packages in different conditions. The fact that the 200 mm packages will probably still hinder the flow of water way longer than the 100 mm welds will lose their integrity, should be also added to the modelling process. One feature already considered was designing a multilayered package, where a stainless steel box would be added to either inner or outer side of the radiation shielding package. This same idea could also be applied to the RPV by instead of welding singular sealing plate per penetration, at least two 20

mm thick plates would be welded per penetration. This would also eliminate the chance of a single weld defect causing a leak.

- An updated animation of the RPV removal process would be beneficial for design concept visualization. This task was left out from the scope of this thesis because, among other things, the Solidworks version that was used to compose the CAD-models displayed some performance issues. If such an animation was created in the future, usage of simplified models, upgraded version of the Solidworks software, or use of animation specified software such as Blender would be recommended.

11 SUMMARY AND CONCLUSIONS

The aim of this thesis was to assess the different RPV decommissioning and disposal concepts of the RPV and the RPVI of the Loviisa NPP and compose CAD-models of the components to be decommissioned. The CAD-model of the reactor was composed based on the existing technical drawings of the Loviisa VVER-440 reactor, and in addition rough models of the facility and decommissioning equipment were created. These models were then utilized to update the previous decommissioning plan considering the decommissioning of the RPV as a whole with new transportation and handling methods of the RPV, as well as more detailed consideration of the long-term durability of the RPV. And as there was no existing plan of segmentation of the components, a plan with assessment of segmentation technologies, methods, and possible locations was made. Additionally, the packages for these segmented components were designed and assessed in terms of radiation and long-term safety. After viable decommissioning plans were done, different aspects of the decommissioning options were assessed and compared based on the overall functionality of the decommissioning process, the time taken on the critical path, the financial costs, the accumulated collective radiation dose, and the long-term dose release rates.

The composed CAD-models of the reactor for the decommissioning purposes were found out to be very useful, in the design process as well as in illustrating the structure of the reactor to third parties. Working with CAD-models instead of 2D-structural drawings offers multiple benefits, as the general view of the components and layout of worksites is much easier to perceive and many of the details needed for the design work e.g., surface-areas and masses can be instantly retrieved from the software. However, direct utilization of the models requires some knowledge of CAD-modelling and when the models get complicated, they tend to require high processing power from the user’s computer as well as a license for the software. This can be somewhat avoided by exporting the models to a 3D-PDF file that is easy to use and will not require a powerful computer to run. In addition to the decommissioning design team, the models will be shared with the facility design team and the radiation safety team, who will utilize them as part of fluid flow modelling and design material for further MCNP-models.

The MCNP-models composed supported the chosen work methods, since in none of the situations modelled were the radiation levels too high to make the working conditions impossible. The models however represent only a few of the critical steps in the decommissioning process and many more models are needed to form accurate and comprehensive radiation dose estimations. As the decommissioned components are highly active, special attention should be paid to the radiation scattering through small gaps, as strong radiation cones could be easily missed from the results. A single missed cone could then cause health hazards with considerably short exposure or damage some electronic components of the equipment used and cause potentially hazardous equipment failures.

The long-term safety of all disposal concepts was found out to fulfil the regulatory limits set by the authorities. Part of this is due to the well-planned existing repository. There are however many details to be considered to make the disposal concepts even better, as the disposal packages were now planned only based on the radiation safety.

Based on the decommissioning and disposal plans presented here, the outcome of the optimal decommissioning option would be the present plan, where no segmentation is done. This is mainly based on the estimated cost and simplicity of the decommissioning option, as well as estimated long-term durability of the RPV as a release barrier. The costs used in the financial estimations are however strongly depended on the overall decommissioning plan of the facility and will change if the decommissioning strategies of other large components change, or if the overall schedule and license of the plant decommissioning allows the segmentation of the RPVI to take place before the fuel is removed from the containment. However, the segmentation of the RPV would not be an ideal choice, as the existing waste repository has already been built to support the transportation of the RPV as a whole and the reactor hall offers somewhat limited space for the segmentation task. Therefore, with further consideration of the decommissioning strategy for the rest of the facility, the option where the RPVI are segmented while the RPV is disposed of as a whole might turn out to be the optimal solution. While segmentation of all the components is internationally a widely used concept, only a small number of decommissioned NPPs have a final disposal repository available. Therefore, this option cannot be directly applied to Loviisa, as long transportation and interim storage of the waste is not required.

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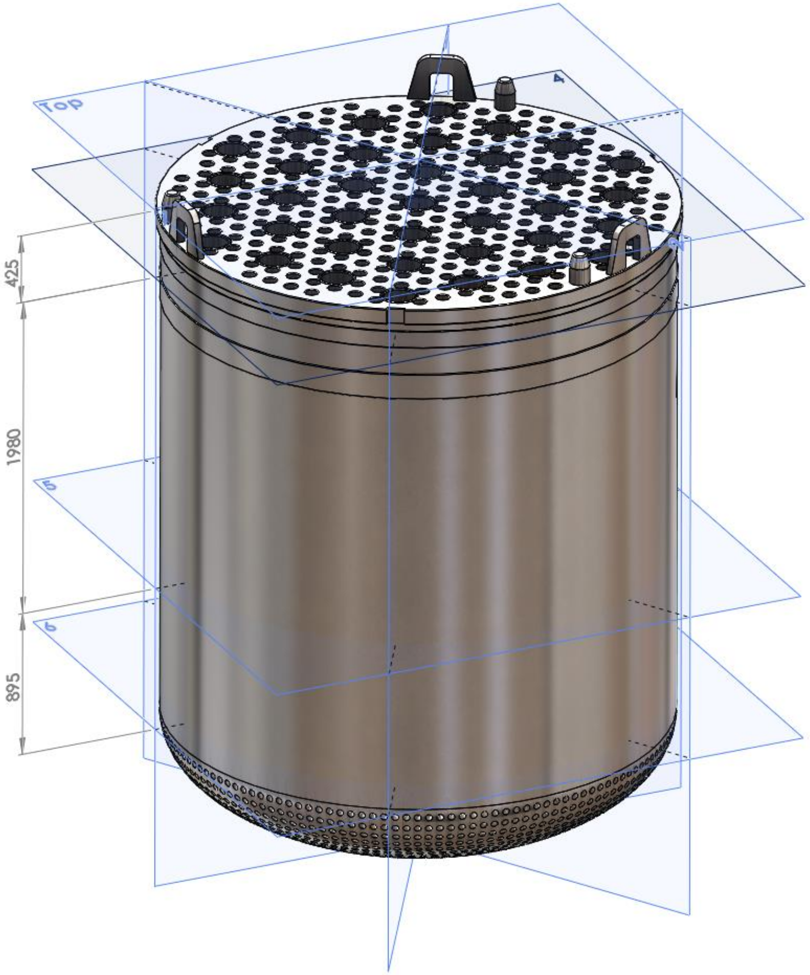
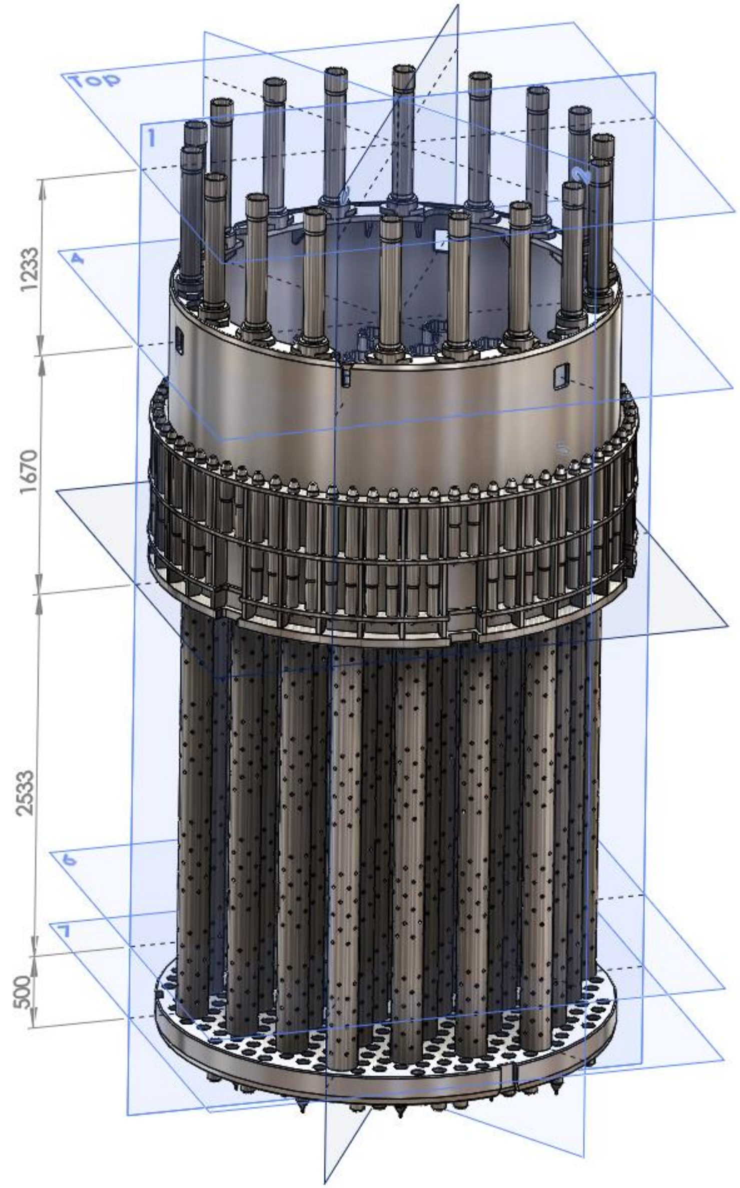
Appendix 1. Activity inventory (Kupiainen et. al., 2019).

Component	**Total activity in 2032 [Bq]**	**C-14**	**Co-57**	**Co-58**	**Co-60**	**Cr-51**	**Fe-55**	**Fe-59**	**Mn-54**	**Mo-93**	**Nb-94**	**Ni-59**	**Ni-63**	**Tc-99**
Half-life		5.73E+03	7.42E-01	1.94E-01	5.27E+00	7.59E-02	2.70E+00	1.22E-01	8.55E-01	4.00E+03	2.03E+04	7.60E+04	1.01E+02	2.11E+05
RPV Cladding	**2.05E+14**	1.56E+11	8.61E+09	7.23E+09	2.73E+13	5.09E+06	1.37E+14	6.26E+07	6.73E+11	0.00E+00	1.83E+10	4.12E+11	3.97E+13	0.00E+00
¼ RPV	**2.74E+14**	1.40E+10	4.27E+08	3.47E+08	2.18E+13	7.96E+05	2.49E+14	1.20E+08	2.78E+12	3.31E+09	0.00E+00	8.57E+09	8.20E+11	2.02E+10
¾ RPV	**7.73E+13**	4.16E+09	4.85E+08	3.61E+08	1.04E+13	1.90E+05	6.39E+13	4.50E+07	2.81E+12	5.57E+09	0.00E+00	2.15E+09	1.90E+11	4.60E+09
Barrel	**7.11E+15**	1.19E+12	3.13E+11	5.29E+11	2.41E+15	1.07E+08	3.80E+15	2.30E+09	5.97E+13	0.00E+00	0.00E+00	8.88E+12	8.32E+14	0.00E+00
Barrel bottom	**2.89E+13**	4.90E+09	1.94E+09	1.55E+09	9.09E+12	4.57E+05	1.60E+13	8.55E+06	1.78E+11	0.00E+00	0.00E+00	3.76E+10	3.55E+12	0.00E+00
Core basket	**2.25E+16**	3.98E+12	5.68E+11	1.15E+12	6.46E+15	3.73E+08	1.30E+16	6.73E+09	1.33E+14	0.00E+00	0.00E+00	3.06E+13	2.92E+15	0.00E+00
Core basket bottom	**2.31E+15**	4.09E+11	1.12E+11	1.76E+11	6.55E+14	3.81E+07	1.33E+15	6.67E+08	2.06E+13	0.00E+00	0.00E+00	3.13E+12	2.99E+14	0.00E+00
PTU	**9.62E+14**	1.66E+11	5.69E+10	7.46E+10	2.95E+14	1.53E+07	5.38E+14	2.84E+08	8.63E+12	0.00E+00	0.00E+00	1.26E+12	1.19E+14	0.00E+00
Shield element	**6.15E+16**	2.11E+13	2.96E+12	8.37E+12	1.01E+16	1.18E+09	4.18E+16	2.51E+10	9.58E+14	0.00E+00	0.00E+00	8.94E+13	8.49E+15	0.00E+00
Control rods	**1.14E+14**	1.97E+10	6.76E+09	8.87E+09	3.51E+13	1.82E+06	6.40E+13	3.38E+07	1.03E+12	0.00E+00	0.00E+00	1.50E+11	1.42E+13	0.00E+00
Metal scrap	**2.70E+14**	3.06E+11	0.00E+00	0.00E+00	1.46E+14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.29E+12	1.22E+14	0.00E+00
Total	**9.53E+16**	**2.74E+13**	**4.03E+12**	**1.03E+13**	**2.02E+16**	**1.72E+09**	**6.09E+16**	**3.53E+10**	**1.19E+15**	**8.88E+09**	**1.83E+10**	**1.35E+14**	**1.28E+16**	**2.48E+10**

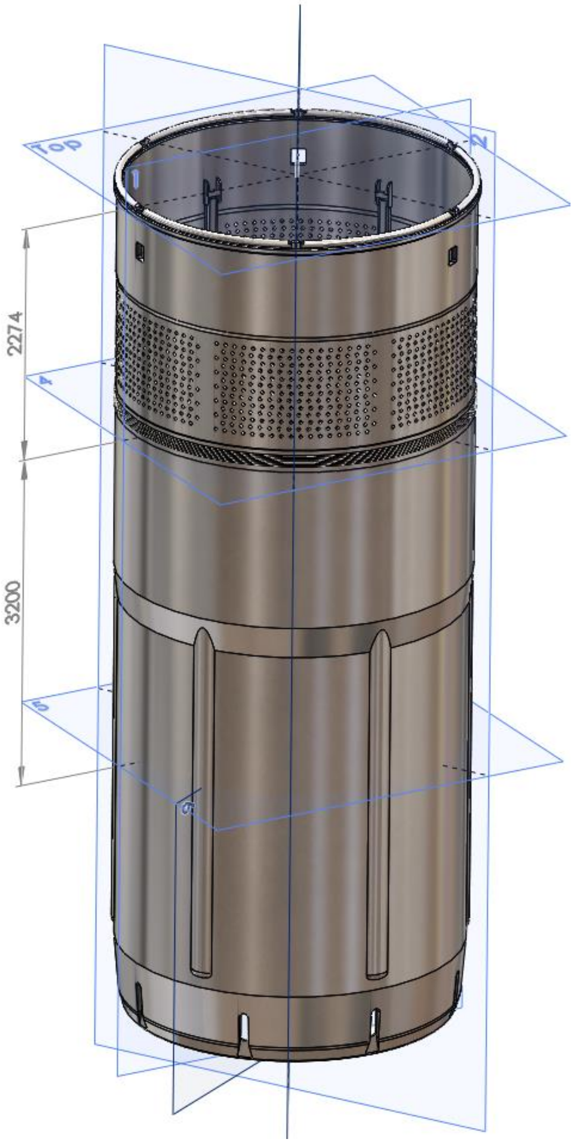
Appendix 2. Component segmentation schemes



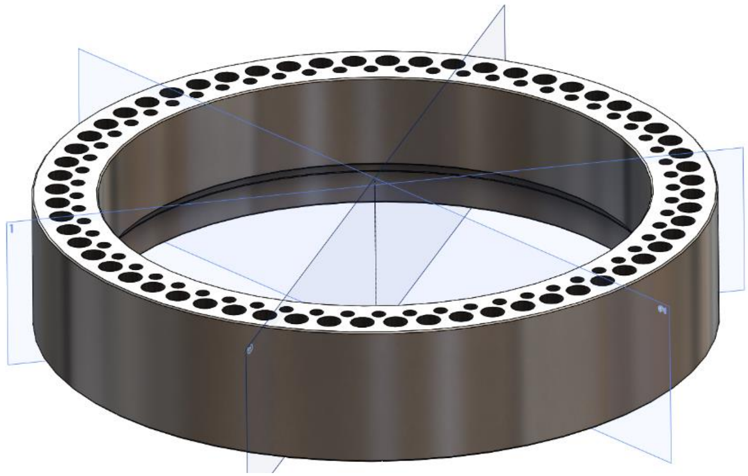
Barrel bottom.



PTU.



Barrel.



Upper flange.

Vessel head.