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UPTEC STS 26045
Examensarbete 30 hp
Maj 2026

Identification of Best Available Techniques (BAT) for the Treatment of Spent Organic Ion Exchange Resins from Nuclear Power Plants

A Comparative Study of Treatment Methods Using a Multi-criteria Analysis

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Civilingenjörsprogrammet i system i teknik och samhälle

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Abstract

The increasing use of nuclear power highlights the need for safe and effective management of radioactive waste. One type of such waste is spent organic ion exchange resins, which are widely used for water purification in nuclear power plants. Several treatment methods for spent organic ion exchange resins exist, but no single method has been established as the most optimal.

This thesis aims to identify the Best Available Techniques (BAT) for the treatment of these resins by applying a weighted multi-criteria analysis (MCA). Four treatment methods are evaluated. These are immobilization in cement, immobilization in bitumen, immobilization in polymers and pyrolysis with subsequent immobilization in cement. The multi-criteria analysis is based on criteria such as technological availability, radiation safety, final waste form quality, secondary waste generation, technical performance, non-radiological safety and economic aspects.

The results of the multi-criteria analysis indicate that immobilization in cement can be considered Best Available Techniques for the treatment of ion exchange resins. The results also show that while identification of immobilization in cement as BAT can be considered robust, the analysis is dependent on the scoring framework and weighting assumptions.

Although a multi-criteria analysis enables a structured comparison of the treatment methods, the results are influenced by methodological choices. Immobilization in cement is favored due to its technological maturity, safety and stable final waste form but is also associated with limitations such as low waste loading. This emphasizes the importance of interpreting the results as indicative rather than absolute, since BAT assessments are context dependent.

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Populärvetenskaplig sammanfattning

I takt med ett ökande globalt energibehov har intresset för kärnkraft ökat i många länder. Samtidigt uppstår radioaktivt avfall vid drift och underhåll av kärnkraftverk. Detta avfall måste tas om hand om och förvaras på ett säkert och hållbart sätt utan risk för människor och miljö. En typ av sådant avfall är använda organiska jonbytarmassor. Organiska jonbytarmassor består av små plastlikande korn eller ett slags pulver och används för att rena vatten i kärnkraftverk, till exempel kyl- eller processvatten. När vatten passerar genom jonbytarmassorna fastnar radioaktiva ämnen och andra föroreningar i materialet. Efter en tids användning måste jonbytarmassorna bytas ut. Jonbytarmassornas egenskaper gör att de inte lämpar sig för direkt hantering, transport eller slutförvaring. De måste därför behandlas innan de kan transporteras vidare till slutförvar.

Det finns flera metoder för att behandla jonbytarmassor. Vissa metoder bygger på att massorna gjuts in i ett lämpligt material medan andra innebär att jonbytarmassorna bryts ned genom exempelvis förbränning. Varje metod har egna för-och nackdelar när det kommer till säkerhet, miljöpåverkan, kostnader och teknisk komplexitet.

Syftet med detta examensarbete är att utvärdera ett urval av behandlingsmetoder för att bestämma vilken metod som kan klassas som Best Available Techniques (BAT), eller Bästa Tillgängliga Teknik på svenska. BAT innebär att en teknik eller metod ska åstadkomma det högsta möjliga skyddet för människor och miljö, samtidigt som den är tekniskt tillgänglig och ekonomiskt genomförbar. För detta används en multi-kritiereanalys där behandlingsmetoder jämförs utifrån utvärderingskriterier som teknisk mognad, strålsäkerhet, miljörisker, resursbehov och avfallsproduktens stabilitet. Som grund för analysen används information som samlats in genom litteraturstudier och expertintervjuer. Det urval av behandlingsmetoder som utvärderas är ingjutning i cement, ingjutning i bitumen, ingjutning i polymerer (plastmaterial) samt pyrolys (förbränning i syrefattig miljö) med efterföljande ingjutning av askan i cement.

Resultatet visar att ingjutning i cement sammantaget presterar bäst i multi-kritierieanalysen och kan identifieras som BAT. Metoden är välbeprövad, säker, tillgänglig och ger en stabil avfallsprodukt som lämpar sig för slutförvar. De andra behandlingsmetoderna kan ha fördelar inom vissa områden som exempelvis minskad avfallsvolym, med dessa fördelar väger inte upp nackdelar som större teknisk komplexitet, mindre praktisk erfarenhet eller lägre säkerhet.

Acknowledgements

This thesis marks the conclusion of my studies at the Master's Program in Sociotechnical Systems Engineering at Uppsala University. It has been carried out in collaboration with AFRY, a consulting company providing engineering, design and advisory services.

My studies have been a long and challenging journey, but also a very rewarding one. I would like to take this opportunity to express my sincere gratitude to those who have supported me along the way.

I would like to extend my deepest thanks to my supervisors Hans Henriksson, Mikael Lindroos and Jesper Grönroos, as well as my subject reviewer Mattias Lantz. Thank you for your guidance, feedback and valuable input throughout this thesis.

I am also very grateful to all interview participants who generously shared their time and knowledge, as well as to the experts in the field who shared their insights.

Finally, I would like to thank my family and my partner, Gabriel, for their unwavering support and encouragement during my studies. I could not have done it without you.

Sofia Olsén Jonsson
Uppsala, May 2026

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Glossary

Abbreviations and Acronyms

CTU – *Container Treatment Unit*.

Gy – *Gray*. SI unit for absorbed dose of ionizing radiation, equal to one joule per kilogram.

HEPA – *High-Efficiency Particulate Air*. A type of air filter.

IAEA – *International Atomic Energy Agency*. International organization promoting safe, secure, and peaceful use of nuclear technologies.

SFR – *Final Repository for Short-Lived Radioactive Waste* (Swedish: *Slutförvaret för kortlivat radioaktivt avfall*). Sweden's repository for low- and intermediate-level radioactive waste.

SKB – *Swedish Nuclear Fuel and Waste Management Company* (Swedish: *Svensk Kärnbränslehantering AB*). Company responsible for management and disposal of radioactive waste in Sweden.

SMR – *Small Modular Reactor*. Advanced nuclear reactor design with smaller power output and modular construction.

Sv – *Sievert*. SI unit for equivalent and effective dose, representing biological impact of ionizing radiation.

WAC – *Waste Acceptance Criteria*. Regulatory and technical requirements that radioactive waste must meet to be accepted for treatment, storage or disposal.

Chemical elements and compounds

^{14}C – Radioactive isotope of carbon.

^{60}Co – Radioactive isotope of cobalt.

^{58}Co – Radioactive isotope of cobalt.

^{90}Sr – Radioactive isotope of strontium.

^{137}Cs – Radioactive isotope of cesium.

^{129}I – Radioactive isotope of iodine

^{235}U – Radioactive isotope of uranium.

^{238}U – Radioactive isotope of uranium.

$CaCO_3$ – Calcium Carbonate (lime)

Cl^- – Chloride ion.

CO – Carbon Monoxide.

CO_2 – Carbon Dioxide.

NaOH – Sodium Hydroxide.

Na_2CO_3 – Sodium Carbonate.

NO_x – Nitrogen Oxides.

SO_2 – Sulfur Dioxide.

H^+ – Hydrogen ion.

1. Introduction

The nuclear power industry is currently undergoing a resurgence. As global electricity demand rises, nuclear power is gaining renewed attention. More nations are incorporating nuclear power in their long-term energy strategies, new reactor designs are advancing and worldwide construction is growing. Small modular reactors (SMRs) are becoming of interest, with the first commercial units expected within the next decade. Existing plants are being refurbished to extend their lifetimes and new reactors are set to enter service in several countries (International Energy Agency, 2025, p.8). An increased reliance on nuclear energy also brings greater attention to the management of radioactive waste. As capacity grows, the need for efficient and reliable waste treatment methods become even more critical.

At nuclear power plants and other nuclear facilities, a variety of liquid processes are used and liquid waste streams are generated. Liquids from these processes require treatment to maintain proper process chemistry or to remove radioactive contaminants. These liquids can include primary reactor coolant, water from spent fuel pools and effluents from radioactive waste handling systems. Among the most widely used methods for treating these liquids is ion exchange. Ion exchange is a well-established technology that has been used for decades in both nuclear operations and other industrial areas. The material used for these ion exchange processes in nuclear power plants is ion exchange resins (IAEA, 2002, p.1). After use, the ion exchange resins contain radioactive nuclides (Li and Chen, 2024, p.3) and become radioactive waste. Ion exchange resins make up around 4% of all solid nuclear waste and about 4000 m^3 of waste consisting of ion exchange resins is produced per year globally (Atkinson et al., 2025, p.1). Since they are radioactive waste, spent ion exchange resins need to be conditioned and treated before storage and final disposal. There are a number of different treatment methods available for this purpose. Each treatment method has its own technical characteristics, advantages and limitations (Li and Chen, 2024). Some treatment methods for ion exchange resins have been practiced for several years, while others are more experimental. Currently, there is no single optimal treatment method for ion exchange resins (Li and Chen, 2024, p.16).

In industrial environmental management (Project Driven, n.d.) as well as radioactive waste management, Best Available Techniques (BAT) is a concept that aims to identify processes and techniques that provide a high level of protection for people and the environment as well as providing safe handling and disposal of radioactive waste while being both technically available and economically feasible (Nuclear Institute, 2010, p.4-5). The identification of BAT is often dependent on context (Nuclear Institute, 2010, p.4) and requires a structured comparison of possible alternatives.

The objective of this thesis is to evaluate a selected set of treatment methods for ion exchange resins from nuclear power plants to investigate their performance and to identify which one can be considered Best Available Techniques (BAT). To achieve this, an extensive qualitative study is conducted to obtain data and information about the selected treatment methods. This information forms a basis for a multi-criteria analysis (MCA) that is used to assess the performance of the selected treatment methods under the defined evaluation criteria.

The scope of this study is limited to organic ion exchange resins from low-to intermediate level radioactive waste streams. The study is also limited to the investigation of treatment methods that are sufficiently developed to be industrially applicable and focuses on the conditioning and treatment of the waste prior to final disposal. The analysis is based on information from literature, technical reports and expert interviews. Economic and resource-related aspects are evaluated at an indicative level. In addition, since multi-criteria analyses are subjective by nature, the results are influenced by choice of evaluation criteria, weights, scoring framework and the information available for each treatment method.

2. Background

This section outlines the framework for radioactive waste management and describes the function and characteristics of ion exchange resins used in nuclear power plants. It also provides an overview of treatment methods for this type of waste. The concept of Best Available Techniques (BAT) is also described in detail.

2.1 Management of radioactive waste and Waste Acceptance Criteria

The management of radioactive waste is an unavoidable part of nuclear operations (IAEA, 2023, p.1). Radioactive waste is classified into categories based on its level of radioactivity, ranging from exempt waste, to low-level waste, to intermediate-level waste to high-level waste (IAEA, 2009, p.5). The handling of radioactive waste is a stepwise process covering both the administrative and practical work needed before disposal of the waste as well as the disposal itself. The IAEA has safety standards that provide the framework that guides countries on how they should plan and operate their radioactive waste management systems. According to the IAEA's fundamental safety principles, the core goal is to protect people and the environment from the harmful effects of ionizing radiation. One of the most important aspects in the management process is establishing and following Waste Acceptance Criteria (WAC), which define the conditions that waste must meet during and after treatment, storage and disposal. The IAEA defines WAC as *"quantitative or qualitative criteria specified by the regulatory body, or specified by an operator and approved by the regulatory body, for the waste form and waste package to be accepted by the operator of a waste management facility"* (IAEA, 2023, p.1). Besides radiological characteristics, WAC also covers mechanical, chemical, biological and other properties of packaged and unpackaged waste (IAEA, 2023, p.1).

In Sweden, the management of radioactive waste is governed by legal framework that establishes clear roles and responsibilities. It defines how licensing, documentation, inspection, control and reporting of these activities is carried out. The laws and regulations place the main responsibility for the safe handling and disposal of radioactive waste on the companies or organizations that hold a license to run nuclear facilities, while the State has overall responsibility for long-term safety. Key laws that regulate the management of radioactive waste in Sweden are the Lag om kärnteknisk verksamhet (Act on Nuclear Activities), Strålskyddslagen (Radiation Protection Act), Miljöbalken (Environmental Code) and Lagen om finansiering av kärntekniska restprodukter (Act on Financing of Residual Products from Nuclear Activities). Together, these acts form a legal structure designed to guarantee that radioactive waste is managed safely, responsibly and sustainably in Sweden. They ensure that proper responsibility for handling and disposing of waste is taken and that radiation risks to people and the environment are minimized. They also ensure that environmental principles such as precaution, the use of best available technology and conservation of natural resources are applied. The framework also requires thorough environmental assessments and long-term planning while also securing financial resources needed for decommissioning and final disposal through a dedicated funding system (Regeringen, 2024, p.19).

Sweden has a repository for low and intermediate level waste called Slutförvaret för kortlivat radioaktivt avfall (SFR). The SFR facility lies beneath the Baltic Sea, under 60 meters of bedrock. The underground repository includes four vaults, each around 160 meters in length. In addition, the repository contains a 70 meter high silo. Waste is placed in specific sections of the facility depending on activity level, composition and chemical properties. The SFR facility is the final disposal site for low-and intermediate level waste such as ion exchange resins (Regeringen, 2024, pp.53-54). Waste deposited at SFR must meet certain acceptance criteria. SFR's acceptance criteria require that the waste meets specified requirements regarding waste type, activity content, physical and chemical stability, package design and documentation to ensure long-term safety. For waste packages containing ion exchange resins the total absorbed radiation dose to the waste form must not exceed 10^6 Gy[1] (SSM, 2017, p.20). This value refers to the total absorbed dose accumulated over the lifetime of the waste form (i.e. over an infinite time period), rather than a dose rate.

2.2 Ion exchange resins

There is a wide range of ion exchange materials available for treatment of radioactive liquids (IAEA, 2002, p.12). These materials can be categorized as either organic or inorganic. The most utilized in the nuclear industry is the organic type. Among the different types of organic ion exchange materials available, resins made from polystyrene divinylbenzene are the most widely used (IAEA, 2002, pp.1-2). Nuclear

[1] A gray (Gy) is the derived SI unit for measuring absorbed dose of ionizing radiation expressed as absorbed energy per unit mass, J/kg.

power plants have traditionally relied on organic ion exchange resins to treat coolant- and process water. Even though inorganic ion exchanges have recently become a possible alternative, inorganic exchangers cannot fully replace organic resins in all nuclear plant applications. Systems requiring high-purity water or precise chemical control still depend on organic ion exchange resins (IAEA, 2002, p.1).

Organic ion exchange resins are insoluble plastic materials made of large molecules connected in a three-dimensional structure. This structure allows them to capture ions from liquids (Li and Chen, 2024). Ion exchange resins can be in bead form, where the resins resemble small plastic beads, or in powder form (IAEA, 1985, p.2). An example of resins in bead form is illustrated in Figure 1. Resin beads are typically 0.3 – 1.2 mm in diameter. These resins are used for ion exchange processes which are essentially chemical reactions where ions from a contaminated liquid are removed and replaced with more desirable ones. Process water in nuclear power plants becomes contaminated as it circulates through systems exposed to corrosion, high temperature and radiation. Corrosion releases metal ions into the water and these ions can become radioactive when passing through the reactor core. Small amounts of fission products may also enter the cooling water in the reactor. Ion exchange resins are used to remove these from the water by selectively binding and exchanging ions (IAEA, 1985, p.3-5).

Figure 1. Ion exchange Resin Beads, (Wikipedia Commons, 2014)

In an ion exchange process, ions from a liquid are exchanged for ions that are electrostatically bound to the functional groups of the ion exchange resin. Ion exchanges are divided into different types depending on their functional groups. When the functional groups are positively charged the exchange involves anions. Conversely, when the functional groups are negatively charged the exchange involves cations (IAEA, 2002, p.5). The reactions for cation exchange are written as

$$2HR^{+} + {}^{90}Sr^{+2} \rightarrow SrR_2 + 2H^{+} \quad \text{(R1)}$$

$$HR + {}^{137}Cs^{+} \rightarrow CsR + H^{+} \quad \text{(R2)}$$

$$2HR + {}^{60}Co^{2+} \rightarrow CsR + H^{+} \quad \text{(R3)}$$

and for anion exchange as

$$RNH_3^{+}CL^{-} + {}^{129}I^{-} \rightarrow RNH_3^{+}I^{-1} + Cl^{-} \quad \text{(R4)}$$

where R represents the functional group in the resin (Li and Chen, 2024, p.2).

After ion exchange resins have been used for treating the different types of liquids at nuclear power plants they are considered spent and contain radionuclides such as ^{60}Co, ^{58}Co, ^{90}Sr, ^{137}Cs, ^{235}U, ^{238}U and ^{129}I (Li and Chen, 2024, p.3). As such, the spent ion exchange resins themselves become radioactive waste that need to be treated and disposed of in a suitable and safe manner. The radioactivity level of the spent resins is typically classified as low to intermediate (Li and Chen, 2024, p.1).

2.3 Treatment methods for ion exchange resins

The treatment and conditioning of spent ion exchange resins can be carried out using either destructive or non-destructive methods or a combination of both. If a combination is used, the destructive method is carried out first.

Destructive methods involve both thermal and non-thermal treatments (IAEA, 2002, p.51). Examples of destructive methods are incineration, where the resins are burned, or pyrolysis where resins are burned in an oxygen-free environment (IAEA, 2002, p. 49). Other destructive methods are plasma techniques, where resins are melted in a plasma furnace (IAEA, 2002, p. 60). Another destructive method is hot pressing, a technique where the resins are compacted into pellets (IAEA, 2002, p. 58). There are also several different types of wet oxidation. These are processes in which the resins are dissolved in water using heat, pressure and oxygen (Wang and Wan, 2015, pp.51-52). Other destructive methods involve using acid digestion, molten salt (IAEA, 2002, p. 62) or microbes (Wang and Wan, 2015, p.54) to degrade and break down the resins. Resins can also be treated using vitrification, a process in which resins are mixed with glass-forming additives and heated to high temperatures, melting the mixture. As the mixture cools, it forms a solid glass material. Vitrification can be used for both intact resins as well as ash from incinerated resins (IAEA, 2002, p. 58).

Non-destructive methods involve either encapsulating the waste in a high integrity container or incorporating it in a matrix material for solidification. The latter is a process called immobilization. The matrix materials typically used for immobilization of resins is cement, bitumen and some polymer materials (IAEA, 2002, p. 60). Cement is defined as a powdered substance that has a strong adhesive power when combined with water (IAEA, 1985, p.16). Cement types commonly used for this purpose are made of calcium aluminates and calcium silicates (IAEA, 1983, p.30). Bitumen is a collective term (IAEA, 2002, p. 74) for dense, viscous petroleum-based hydrocarbons (Britannica, 2017) with high molecular weight. It is essentially a dark, almost solid form of petroleum, often used as a binder in asphalt. Polymers used for immobilization are plastics like polyethylene, epoxy resins, polyester resins and urea-formaldehyde (Richard, 2024, p. 7). In an immobilization process, the waste is mixed with the matrix material at either ambient temperatures or high temperatures. As the mixture hardens it forms a solid material in which the resins are incorporated and immobilized.

There is currently no treatment method for ion exchange resins that has been established as a primary international industry standard. Each treatment method faces its own challenges and benefits. In addition, the available treatment methods for ion exchange resins are all in different stages of development and industrial establishment. For example, methods using molten salt (Li and Chen, 2024, p.16) and wet oxidation are still in early-development stages (Wang and Wan, 2015, pp.51-52) while immobilization methods have been used for decades (IAEA, 1985). In fact, immobilization in cement has been highlighted as the standard method for conditioning low and intermediate-level waste (Fernández et al., 2025, p.1). This indicates that non-destructive methods remain the most widely applied approaches today. The main methods used for treatment of spent ion exchange resin in Sweden is immobilization in cement or bitumen.

2.4 Best Available Techniques (BAT)

BAT is an abbreviation of Best Available Techniques. It is a fundamental concept in environmental regulation and industrial environmental management. In general, BAT refers to the most effective techniques for preventing or minimizing environmental impacts from industrial activities, while remaining technically and economically feasible (Project Driven n.d.). In the nuclear waste management industry, BAT is defined as "*the latest stage of development of processes, facilities, or methods of operation that demonstrate the practical suitability of a particular measure for limiting waste generation and waste disposal"* (Nuclear Institute, 2010, p.4). The concept of BAT rests on three pillars:

- **Best:** Refers to the most effective technique in achieving a high level of protection of the public from the exposure of ionizing radiation (Nuclear Institute, 2010, p.5) as well as ensuring a high level of environmental protection from emissions and pollution (Project Driven n.d.).
- **Available:** Refers to whether the technique or technology has been developed and demonstrated at a scale suitable for the relevant industrial sector and is both technically and economically viable (Nuclear Institute, 2010, p.5).
- **Techniques:** Refers to both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned (Nuclear Institute, 2010, p.5).

3. Objectives and research questions

The objective of this thesis is to, with the support of a multi-criteria analysis (MCA) based on weighted evaluation criteria, identify the Best Available Techniques (BAT) for the treatment of waste in the form of spent organic ion exchange resins from nuclear power plants. Four treatment methods have been identified as candidates for this evaluation. These are:

- Immobilization in cement.
- Immobilization in bitumen.
- Immobilization in polymers.
- Pyrolysis and immobilization in cement.

The research questions for this thesis are:

- How do the identified treatment methods perform in a multi-criteria analysis (MCA)?
- Which of these treatment methods can be identified as the Best Available Techniques (BAT) based on the results of the multi-criteria analysis?

4. Method

This thesis uses a combination of literature review, expert interviews, correspondence with industry experts and a structured multi-criteria analysis (MCA) to evaluate treatment methods for spent organic ion exchange resins from nuclear power plants in order to determine which method can be identified as Best Available Techniques (BAT). A qualitative study was conducted to gather detailed information about the treatment methods and the resulting waste forms. The foundation of this study consisted of interviews with subject-matter experts, technical and scientific reports as well as peer-reviewed articles. No experimental testing or trials have been done. Consequently, the assessment relies on available published data and qualitative information from experts which may vary in detail between treatment methods.

The primary literary sources used for this study are technical reports from established organizations such as the IAEA. Reports from such institutions have been considered reliable due to their authority within the nuclear industry and radioactive waste management. However, some of the reports used are older and may contain somewhat outdated information. The scientific articles and reports used have been peer-reviewed and are considered as scientifically valid. Governmental reports are regarded as reliable since they are produced under legal and regulatory frameworks. Information from private industry stakeholders and organizations provides useful insight but may reflect organizational perspectives and are therefore interpreted with caution.

4.1 Multi-Criteria Analysis (MCA)

Multi-criteria analysis, also referred to as multi-attribute analysis, is a collective term for methods used to systematically structure and evaluate different alternatives in decision-making situations where multiple criteria or objectives are relevant simultaneously (Back et al., 2009). The method is useful in decision-making situations where the relevant criteria cannot be reduced to a single measure. (Department for Communities and Local Government, 2009) Multi-criteria analysis has also been highlighted as a tool to identify BAT (Nuclear Institute, 2010, p.28). Multi-criteria analysis is a decision-oriented form of evaluation that enables the comparison of alternatives by aggregation how well each option performs against established evaluation criteria (Department for Communities and Local Government, 2009).

The multi-criteria analysis used in this thesis is based on a linear additive model. In a linear additive model, the evaluation criteria are weighted according to their relative importance. The alternatives, j, (in this case the different treatment methods) are scored based on how well they fulfill the evaluation criteria, i *(i=1…N)*. The final score for each treatment method is calculated by multiplying the criterion score, R, by the corresponding criterion weight, W, and summing the results according to

$$Final\ score_j = \Sigma_{i=1}^{N}(W_i R_{i,j}) \qquad (1)$$

The treatment methods are scored 1-5 where 1 represents the lowest performance and 5 the highest performance. The weights also range from 1-5 where 1 represents the lowest importance and 5 the highest. The treatment method that receives the highest final score is the one that is identified as BAT.

The evaluation criteria for the multi-criteria analysis were developed based on a broad understanding of what aspects of treatment processes and waste characteristics are considered important when assessing treatment methods for radioactive waste. This understanding developed through recurring areas of interest identified during the early phase of the project and common aspects highlighted in literature and reports as well as principles used in assessments of BAT such as technical availability, economic viability and environmental protection. Although they are not derived from a single source, the criteria reflect aspects that consistently appear relevant in both waste management and BAT-evaluations. These criteria formed the basis for the multi-criteria analysis used to assess the treatment methods and determine which option can be considered BAT under the conditions studied. In total, 7 criteria were developed. These, along with their assigned weights, are listed in table 1.

Table 1. Evaluation criteria and assigned weights.

Criterion, i	Weight, W_i
Technological availability and maturity	4
Technical performance	3
Secondary waste generation	3
Radiation safety	5
Safety and environment	4
Final waste form quality	5
Economy and resource efficiency	2

Technological availability and maturity assesses whether the method is sufficiently developed, proven and implementable. *Technical performance* evaluates how efficiently the method operates, including production rate, effect on waste volume and the need for pretreatment and additives. *Secondary waste generation* considers whether the method produces additional waste streams such as off-gases, residues or other by-products that require further handling. *Radiation safety* considers potential radiological risks during treatment, including radiation exposure and the risk of radionuclide spread or release. *Safety and environment* covers non-radiological risks such as potential occupational hazards, chemical hazards and fire hazards. *Final waste form quality* assesses the suitability of the treated waste for long-term disposal focusing on stability, radionuclide retention, resistance to environmental factors and mechanical strength. *Economy and resource efficiency* evaluates costs and resource use including aspects such as materials, energy demand, staffing and maintenance requirements.

The weighting of the criteria reflects their relative importance within BAT principles and the context of management of radioactive waste. *Technological availability and maturity* was given a weight of 4 because a treatment method must be sufficiently developed, established and implementable to be considered a BAT candidate. *Technical performance* received a weight of 3, acknowledging that production rate, volume change and process demands are important but secondary to safety and availability. *Secondary waste generation* also received a weight of 3 since waste minimization is favorable but less critical than safety and availability. *Radiation safety* was assigned the highest weight since minimizing exposure to ionizing radiation and preventing the spread of radionuclides are fundamental regulatory and BAT requirements. *Safety and environment* received a weight of 4, reflecting the importance of minimizing non-radiological risks and hazards during treatment as well as environmental impact. *Final waste form quality* was given a weight of 5 since long-term stability and integrity of the final waste form in repository is essential. *Economy and resource efficiency* was given a weight of 2. Economic viability is part of BAT assessments, but it must not outweigh safety, environmental protection or long-term performance of the final waste product.

4.2 Sensitivity analysis

In order to investigate the sensitivity and robustness of the results from the MCA, a simple sensitivity analysis will be conducted. In this analysis, the scores for each treatment method in each criterion will be varied by ±1 and criteria weights will also be varied by ±1. This will be done while respecting the boundaries of the scoring scale and the weighting scale (1-5). The total scores will be recalculated according to equation (1).

4.3 Delimitations

The study is limited to organic ion exchange resins. Inorganic ion exchange resins are not considered as they are not used to the same extent in the industry and are generally treated using non-destructive treatment methods. The study also focuses on resins classified as low-and intermediate-level radioactive waste, since these are the dominant category of spent ion exchange resins and are relevant for disposal in facilities such as SFR in Sweden. The four treatment methods were chosen based on earlier research found in the article *Optioneering in nuclear ion exchange resin disposal* (2025) by C.M. Atkinson et al. This article highlights these treatment methods as relevant candidates for evaluation based on data availability, technology readiness level and rollout time estimate. Based on this, the four treatment methods were deemed realistic candidates for BAT-evaluation (Atkinson et al., 2025, p.9). Other treatment methods were excluded based on their development level and establishment in the industry, since availability is a core aspect for a treatment method to be considered BAT. The thesis was also limited to these four treatment methods based on time-limit, the scope of the thesis, amount of available information, as well as access to expert knowledge and interviewees.

Economic aspects are evaluated at an indicative level. The study focuses on material costs, energy use and resource demands but does not include life-cycle costs analysis or investment cost analysis. The BAT concept includes assessment of the entire technique including design, construction, installation and decommissioning. This study is limited to the evaluation of the treatment methods themselves and focuses on their process steps, technical performance and resulting waste forms.

4.4 Interviews

Semi-structured digital interviews were conducted as part of the qualitative study. Three industry professionals were interviewed. An interview guide with predefined questions was used and follow-up questions were asked when needed. The interview guide can be found in appendix A. The information obtained in the interviews reflects the interviewees' professional experiences. While information from interviews may contain subjective assessments, it also provides valuable information about the treatment methods not found in literature. The persons interviewed for this thesis were Anders Höglund, Björn Bartholdsson and Dr. Per Lidar.

Anders Höglund was interviewed about immobilization in cement. Höglund is a senior consultant at AFRY and has previously worked at Ringhals nuclear power plant in Sweden as a specialist in nuclear waste management where he specialized in cementation and emissions minimization.

Björn Bartholdsson was interviewed about immobilization in bitumen. Bartholdsson has worked at Forsmark nuclear power plant in Sweden since 2011 and currently has a position as waste management coordinator at Forsmark 3.

Dr. Per Lidar was interviewed about pyrolysis. Dr. Lidar works at Studsvik AB as a senior advisor in waste management. Studsvik AB is a Swedish supplier of technical solutions and services to the nuclear industry and has developed a pyrolysis technique called inDRUM (Studsvik, 2025).

5. Qualitative study and data for analysis

The following chapter includes information and data gathered from literature, reports, interviews and correspondence with industry professionals and provides the qualitative basis for this thesis.

5.1 Immobilization in cement

5.1.1 Technology overview

Immobilizing radioactive waste from nuclear power plants in cement is a technique that has been used for decades (IAEA, 1985, p.15). The technical report *Treatment of spent ion exchange resins for storage and disposal* published by IAEA in 1985 describes cement as having many favorable qualities. It is widely used in engineering, it is readily available, processing equipment can be based on conventional technology and the raw material is cheap, according to IAEA's assessment. Moreover, cement is non-combustible, radiation resistant and has a high density, which provides radiation shielding. It is also described as having a reasonable chemical stability (IAEA, 1985, p.15). Other beneficial characteristics of cement is its mechanical strength and relative simplicity of handling. Immobilization in cement as a treatment method for nuclear waste has been used on an industrial scale in many countries over a long period of time (IAEA, 1983, p.30). Countries that have used cementation as a treatment method of radioactive waste include Austria, Belgium, Germany, France, India, the Netherlands, Norway, South Africa, Sweden, Switzerland, United Kingdom and the USA. In

Switzerland, Germany and Sweden, immobilization in cement has been used as a treatment method for spent ion exchange resins (IAEA, 1983, pp.50-53). There are many types of cement that can be used for this purpose and there is ongoing research into the topic.

5.1.2 Treatment processes

The process of cementation is usually carried out as a batch operation directly in the final storage container. The storage container could be a reinforced concrete container or a drum. In most cases some or all of the water used to transport the spent resins as a slurry is used as mixing water for the cement. The ion exchange resins and cement are mixed in the container. Mixing can be done either by using a powered paddle, by rotating the container or through a fixed paddle combined with a rotating container. An example of a cementation process is visualized in Figure 2.

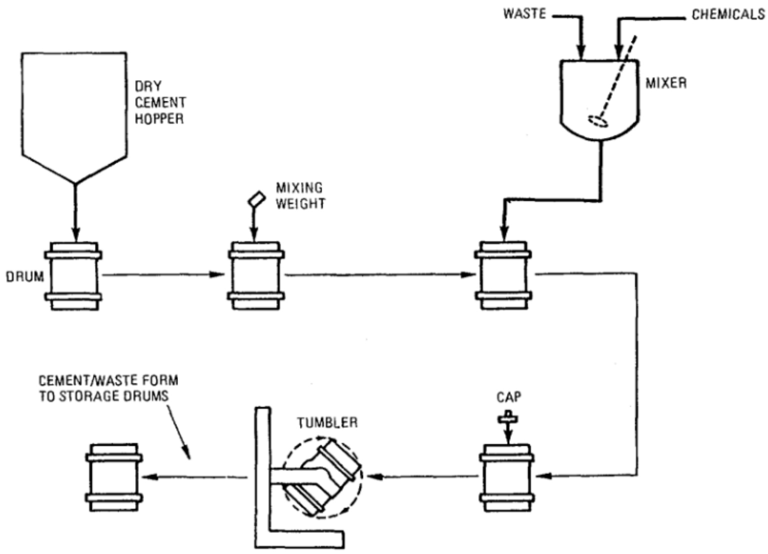

Figure 2. Example of in-drum mixing process, (IAEA, 1983)

After mixing, the cement is allowed to set and solidify. It is crucial to control the ratio of water and resin in order to ensure an acceptable quality of the solidified product. The cementation process is usually performed behind appropriate shielding or in a hot cell facility (IAEA, 2002, p.72).

5.1.3 Waste form characteristics

The compressive strength of cement, if formulated properly (IAEA, 2002, p. 84), is 100-300 kg/cm^2 (IAEA, 1985, p.52). One drawback of this immobilization material is the achievable waste loading, meaning the amount of waste that can be incorporated into the material. This means that the final waste volume is high compared to the initial volume of the spent ion exchange resins. The waste loading of ion exchange resins in cement has been determined to be 10-25% dry resin weight. Pretreating the resins by grinding them could however increase the possible waste loading (IAEA, 2002, p.84). When dry organic ion exchange resin beads come into contact with water they can reabsorb the water and swell. This proves to be another disadvantage to this immobilization method since the swelling of the resin beads may lead to the cement, and the container, becoming damaged and cracked (IAEA, 2002, p. 68). This could pose a problem for the acceptability of the waste form in final depository. The amount of swelling depends on the quantity of resin mixed with the cement, resin quality cement type and water/ cement ratio (IAEA, 1985, p.21). This type of problem does not occur with powder resins due to their small size and therefore it is generally recommended that bead resins should be treated with a pretreatment method such as grinding before cementation (IAEA, 2002, p. 68). Another aspect that needs to be taken into consideration is boric acid content. Spent ion exchange resins from pressurized water reactors may contain boric acid which can affect the setting of the cement. Resins containing boric acid will generally result in an end product with lower waste loading (IAEA, 2002, p.72).

Cement is resistant to biological degradation, meaning that it will not be broken down by microorganisms over time (IAEA, 2002, p. 85). Neither is it flammable (IAEA, 2002, p. 86) and the final waste form is resistant to temperatures over 400° C. Radiation is known to degrade organic materials, causing them to become mechanically unstable. This degradation process also generates hydrogen gas and methane gas that can cause the waste container to crack (IAEA, 2002, p. 88). Cement has been reported to be stable up to absorbed radiation doses of about 10^8 Gy (IAEA, 1985, p.52). This value refers to the total absorbed dose in the material (energy deposited per unit mass). It is the cumulative dose over time, rather than a dose rate or an external measurement.

Another characteristic to investigate when evaluating treatment methods for nuclear waste is leaching behavior of the final waste form. Leaching is when radionuclides are released from a solid material into a medium, usually water. From a final disposal perspective it is important to know the leaching behavior of waste forms, should there be a situation where the waste comes into contact with water in a final repository or during transport. The ability of the immobilizing material to retain radionuclides is therefore an important property. To determine the leach rate of a material, such as cement, leach tests are conducted (IAEA, 1985, p.27). Results from leach test on radioactive waste immobilized in cement has been summarized by the IAEA. In these tests, leaching is evaluated by measuring the amount of radionuclides released from a solid waste form into water over time. To compare leach rates between specimens of different sizes and shapes, a geometry-normalized cumulative leach parameter is used. This geometry-normalized cumulative leach parameter is defined as

$$\frac{2A_n}{A_0} \times \frac{V}{S} \qquad (2)$$

where A_n is the cumulative radionuclide release, A_0 is the amount of radionuclides within the material, V is the specimen volume and S is the exposed surface area (IAEA, 1985, p.15). The term *(V/S)* accounts for the fact that leaching occurs through the exposed surface area. Samples with larger surface area relative to their volume generally exhibit greater radionuclide release. By incorporating the volume-to-surface-area ratio, the influence of specimen geometry is reduced, which allows for more accurate comparisons of leach rates between different waste forms.

Because the geometry-normalized cumulative leach parameter includes the *(V/S)* ratio the leach rates are expressed in units of length (cm). The leach rates should not be interpreted as the fraction or percentage of radionuclides released from the waste form. Instead, they represent a geometry-normalized measure of *radionuclide mobility* within the material. Higher values indicate greater radionuclide release relative to the specimen geometry and therefore a lower radionuclide retention by the waste form.

For cement waste forms, the IAEA reports leach rates after 100 days of 0.2-1 Cs, 1-5×10^{-4} Co, less than 1×10^{-2} Ce and less than 1×10^{-3} of ^{14}C (IAEA, 1985, p.52). These leach rates indicate that Cs is considerably more mobile in cement than the other radionuclides considered. Again, these values do not imply that 20-100% of all Cs has been released after 100 days. Rather, they show that Cs exhibits higher leachability in cement compared to Co, Ce and ^{14}C.

5.1.4 The cementation process at Ringhals nuclear power plant

At Ringhals nuclear power plant, spent ion exchange resins have been immobilized in cement since 1974. The cementation facility is illustrated in Figure 3. The ion-exchange resins are transported from the reactor building Ringhals 1 to the treatment facility through pipes using water and air. This system does not require pumps. Pumps are avoided due to the risk of ion exchange resins getting stuck and forming a blockage, which could lead to problems with protection from radiation. The spent ion exchange resins are then stored in reception tanks before treatment. At the facility, different reception tanks are used for different types of ion exchange resins. The cementation of the resins is done in batches. The industrial equipment needed for cementation of ion exchange resins at this facility is reception tanks, measuring tanks, molds, mixing equipment and pipes for transferring the mixture between containers and into the molds (Höglund, 2026).

The first step in the cementation process is transferring the spent ion exchange resins from the reception tank to a type of measuring tank using compressed air. The mix of resin and water in the measuring tank is dropped into the mold by opening a valve at the bottom of the tank. This is done several times according to a recipe as Höglund puts it. The recipe depends on how many kg of ion exchange material and the amount of water and cement that is needed to achieve a good product. The water from the measuring tank is not enough so extra water is added through the measuring tank. This water also cleans the tank and pipes from radioactivity. After this, mixing starts. During the mixing, cement and lime (calcium carbonate) are added into the resin-water mixture. After the amount of cement that is needed according to the recipe has been added, the mixing continues for about half an hour. Each mold can contain up to 1600 kg of cement but no more than 250-300 kg of dry ion exchange resins, depending on the type of resin. The contents of the mold are mixed with a type of build-in paddle which, after the mixing is complete, is left in the mold therefore it is called a “lost paddle” technique. The paddle then acts as a structural reinforcement in the mold. After the contents of the mold have been thoroughly mixed, the cement is allowed to set and harden. The hardening starts after about 3-4 hours. The amount of time it takes for the mixture to fully harden depends on the contents of the mixture. Ion exchange resins from pressurized water reactors can contain boric acid which inhibits the hardening of the mixture. When immobilizing ion exchange resins that contain boric acid, the proportion of cement to the proportion of ion exchange resins needs to be greater, which impacts the waste loading. Because of this, ion exchange resins which contain boric acid are mixed with ion exchange resin that do not contain boric acid. In this way, the amount of resins that can be cemented in each mold is optimized. With resins containing boric acid the hardening time aimed for at the facility is 24 hours (Höglund, 2026).

The molds are transported through the facility on a track. After completing the mixing procedure, the molds are taken to a place in the facility where the cement is allowed to further set and harden over the course of 48 hours. After this, a concrete lid is cast on top of the mold. This lid-casting process is also done in batches. Special concrete is poured on top of the mold, forming a smooth surface, and is allowed to harden. This procedure requires equipment such as a mixer. The lid-molding process requires that there is no water on the top surface of the mold. There are situations where water could collect on the top of the mold. This water would pose a contamination risk since it would be radioactive. Because of this, the molds are monitored during the hardening process and the temperature of the mold is measured in order to determine if there is water on the top surface. If there is no water on top of the mold, all radioactivity is contained in the cement. After the concrete lid has been cast the mold is left for some time, allowing the lid to harden. The resulting product is “clean” mold, meaning that there are no radioactive particles on either side nor the top lid, according to Höglund. After the cementation process of the ion exchange resins is complete, the molds are kept in storage before they are transported to SFR in Forsmark.

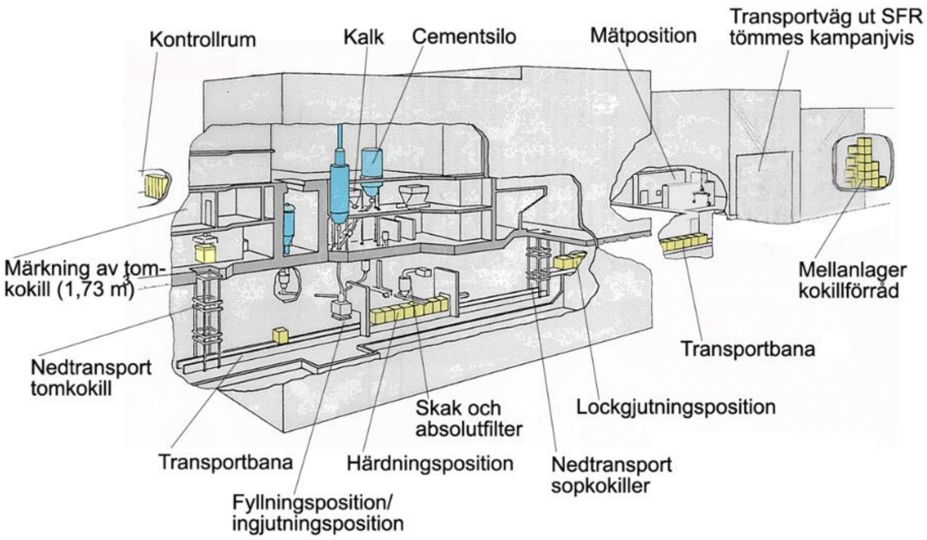

Figure 3. Illustration of the cementation facility at Ringhals, (KSU, n.d.), used with permission.

According to Höglund the amount of molds produced at the facility varies. At the moment, about one mold is produced per day. When all four reactors at Ringhals were still in operation, the facility produced around 60 to 70 molds per year. As mentioned before, Ringhals has used immobilization in cement as a treatment method for spent ion exchange resins since the 70's and Höglund views the treatment method as well-proven. At Ringhals, resins of low-and intermediate activity level have been immobilized in this way. The characteristics of the ion exchange resins need to be thoroughly investigated since variation in resin composition may affect the hardening of the cement. Another aspect of the resins that needs to be closely monitored is their swelling properties. Resins have a tendency to reabsorb water which causes them to swell. This swelling can be so significant that the cement and the surrounding mold crack. To prevent the resins from reabsorbing water, an additive is added to the mixture in the cementation process. At Ringhals, cementation tests of the resins are done regularly. Something Höglund mentions as beneficial with this treatment method is that the process results in no or very little by-products and it does not produce any radioactive secondary waste. Lime and cement powder produce dust which is collected by filters in the ventilation system. There are no emissions caused by the process. The ion exchange resins are always covered with water when stored in tanks before the cementation process which means that there is no risk of activity spreading through the air, according to Höglund. The cementation process is screened off from workers. During normal operation there are no workers in the facilities where the process takes place. Operators control the cementation process from a control room and nobody accesses the areas where the ion exchange resins are stored in tanks. This means that under normal operation, there is no exposure of workers to ionizing radiation and no risk of radioactive particles spreading.

As mentioned, cement powder and lime produce dust when handled and lime is corrosive, but since workers never come into contact with it this does not pose a health risk.

Regarding costs for this treatment method, the molds pose the greatest expense according to Höglund. He estimates that the molds cost about 20 000 kr each. He also estimates that the cement used for immobilizing the ion exchange resins has a market price of about 3-4 kr per kg and the cement used for the lids costs about 6-8 kr per kg. As stated earlier, the Ringhals facility uses up to 1600 kg of cement per mold. As for the lids, about 300 kg is needed. Höglund also states that there has not been any great costs relating to maintenance of the facility and equipment, other than a renewal of the cementation line done in 2008. Operating the facility only requires one worker. When it comes to energy consumption, a small amount of electricity is needed for motors used in the mixing stages, but the treatment method requires no energy for heating of the materials used or similar (Höglund, 2026).

5.2 Immobilization in bitumen

5.2.1 Technology overview

Bitumen has been used for the immobilization of radioactive waste for many years (IAEA, 1985, p.31). Countries where waste has been immobilized in bitumen include Sweden, Finland, USA, France, Belgium, Czech Republic, Denmark, Switzerland and Japan (Richard, 2024, p.2). There are many different types of the material commercially available for immobilization of spent ion exchange resins, according to the IAEA. Bitumen has been used for immobilization of spent ion exchange resins because it has beneficial characteristics such as being insoluble in water, good ageing qualities and good chemical stability (IAEA, 2002, p. 74). It is also described by the IAEA as a material that is readily available at a reasonable cost (IAEA, 2002, p. 74). Bitumen does have some characteristics that need to be taken into account when using the material. Bitumen can react with oxidizing materials and has a lower stability to absorbed radiation doses compared to cement. It also becomes more viscous at higher temperatures. It is a combustible material, although not flammable at temperatures below 290°- 350° C (IAEA, 2002, p.74).

5.2.2 Treatment processes

Before ion exchange resins are immobilized in bitumen some pretreatment procedures are required. Typically, if the resins are in bead form they are grinded. The resins are also dried or dewatered before immobilization. The bituminization process can be carried out as a continuous process or a batch process. The continuous processes typically use film evaporation systems or extrusion systems. When using a film evaporation system, bitumen and ion exchange resins are introduced separately at the top of the evaporator where the two streams of material combine and descend down a heated wall. As the mixture flows downward its water content gradually evaporates. The resulting bituminized waste is drained into containers where it cools and solidifies. The vapors produced are condensed in the evaporator's integrated condenser and then further in a secondary condenser (IAEA, 2002, p. 75). An example of a film evaporator system is illustrated in Figure 4.

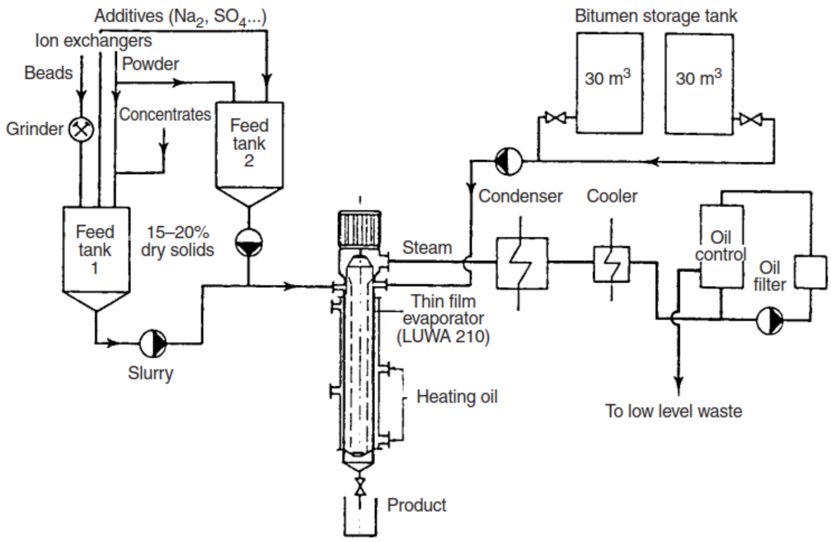

Figure 4. Bituminization system of spent ion exchange resins at Barsebäck nuclear power plant, Sweden, (IAEA, 2002)

In an extrusion process the process is carried out differently than in a film evaporation process. In an extrusion process resins are dried and then introduced into an extruder along with bitumen that has been heated to about 200° C. An example of this type of process is illustrated in Figure 5. As the materials move through the heated extruder, they are thoroughly mixed whilst any remaining water is evaporated. The bituminized material is then poured into drums where it cools and solidifies.

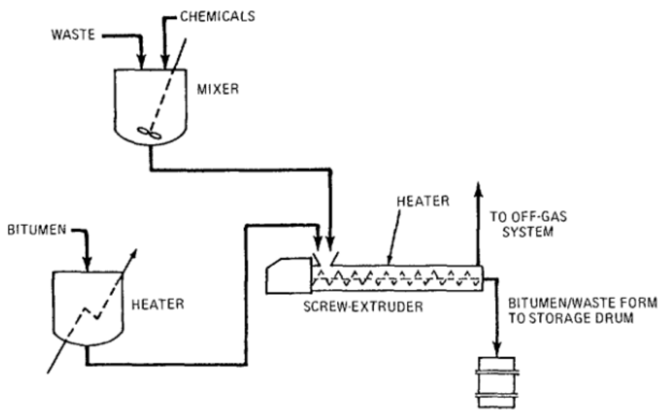

Figure 5. Screw extruder evaporator process, (IAEA, 1983)

In a batch bituminization process, dried ion exchange resins are fed into a controlled quantity of molten bitumen maintained at about 200° C. The resins and the bitumen are mixed in an externally heated mixing tank. Any remaining moisture evaporates as the resins are mixed into the bitumen. Once the desired formulation of the waste mixture is achieved, the feed of resins into the bitumen is halted. The mix continues to be stirred to remove moisture, after which it is poured into containers or drums where it is allowed to cool and harden (IAEA, 2002, p. 76).

5.2.3 Waste form characteristics

The mechanical stability of the final waste form depends on the container since bitumen will soften under pressure or heat. Therefore, the compressive strength of bitumen is considered poor due to its plasticity. Since bitumen is insoluble in water, the final waste form offers strong resistance to water. However, if the material is submerged for a prolonged period of the time the ion exchange resins could reabsorb water leading to swelling which could compromise the integrity of the waste form. Bitumen has a high incorporation capacity of waste, meaning that larger quantities of ion exchange resins can be incorporated in the final waste form. The waste loading for bitumen is around 25-50% dry weight for organic resins (IAEA, 2002, p.84) which is higher than cement and could lead to high volume reduction of the total amount of final waste (IAEA, 2002, p.74). Even possible incorporation of 50-60% of dry resin has been reported (IAEA, 1985, p.52). The resistance to biodegradation of the final waste form is considered moderate (IAEA, 2002, p.84). Research has shown that while bitumen is resistant to fungal- and bacteriological attacks, bitumen samples exposed to molds have shown microscopic changes on the surface (IAEA, 1985, p.33). The final waste form will start to melt at around 220°-250° C, meaning it has a lower heat tolerance than cement (IAEA, 1985, p.52). For bitumen, it has been shown that the cumulative leach fraction per cm over 100 days of Cs is 5×10^{-3}- 10^{-2}, 4×10^{-4}-10^{-3} for Co and 2×10^{-3} for ^{14}C which is overall higher leach rates than cement (IAEA, 2002, p.84). The leach rate for Cs, however, is much lower for bitumen than cement. Experiments have shown that bitumen remains stable up to absorbed radiation doses of approximately 10^7 Gy, meaning that it is a suitable material for treatment of low-to intermediate level wastes (IAEA, 1985, p.43) although not as stable as cement.

5.2.4 The bituminization process at Forsmark nuclear power plant

At Forsmark nuclear power plant in Sweden, immobilization in bitumen is used as treatment method for spent ion exchange resins. At the Forsmark facility, ion exchange resins in powder form mixed with water are stored in tanks (Bartholdsson, 2026). This slurry is then pumped from the tanks into a dryer. This dryer consists of a tank with a heated mantle and a stirrer. The dryer is heated to 150° C in order for all water to evaporate. More ion exchange-slurry is pumped into the dryer in batches until the amount of dry ion exchange resins is large enough to be transferred over to the mixing vessel, which is another heated tank equipped with a stirrer. In the mixing vessel the dry resin powder is mixed with bitumen that has been heated to 150° C. The waste loading of resins in bitumen is about 40-60% depending on the type of ion exchange resin that is being processed. The contents of the mixing vessel are mixed for about 30 minutes until a homogeneous mixture is achieved. The mixture is then drained into a metal mold. The molds are cubic metal containers measuring 1,2×1,2×1,2 meters. The entire process is then repeated 1-2 times depending on the size of the batches since the dryer and mixing vessel do not have the capacity to process the total amount of ion exchange resins and bitumen that can be contained in one mold in one go. Each mold has capacity to contain up to 3 batches of bituminized ion exchange resins but the total amount can vary (Bartholdsson, 2026). After the ion exchange resins have been immobilized in bitumen, the mold is left to cool for a period. Then, it is inspected for radioactive contamination and subsequently taken to storage before being transported to SFR (Grönroos, 2026). A bituminization process very similar to the one at Forsmark is illustrated in Figure 6.

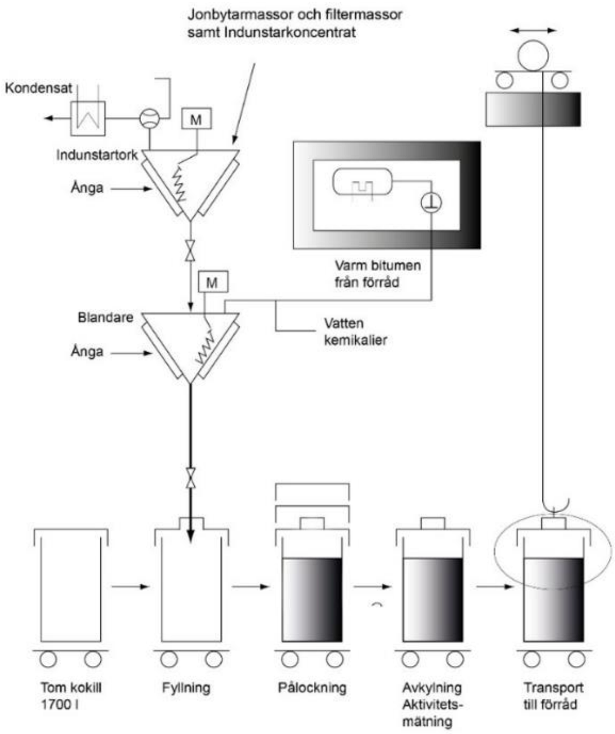

Figure 6. Example of a batch bituminization process, (KSU, n.d.), used with permission.

The treated ion exchange resins swell when they come into contact with water and this needs to be taken into account when using this treatment method. The possible degree of swelling of the resins determines the amount that can be contained in each mold. Another aspect that determines the amount of resins that can be contained in the final waste form is activity. The higher the activity of the resins, the smaller the amount that can be contained in each mold. The amount of waste allowed in each mold has gradually been reduced as new insights into the properties of the resins and their implications for long-term disposal have emerged. A layer of cement is needed at the bottom of the molds to reduce the acidity level of the waste, reducing the loading capacity of bituminized resins in the mold. In total, each mold can contain up to 900 kg where about 400 kg is spent ion exchange resins.

The rate at which waste is treated at this facility fluctuates. After being received at the facility, the waste can be stored in tanks for up to 10 years depending on the waste's characteristics. The amount of time it takes for the bituminization process to be completed depends on the type of waste that is being treated. Depending on the type of ion exchange resin and the amount the time required for drying and production of finished molds also varies but according to Bartholdsson around 1-2 molds are produced per week during normal operations. This method for immobilization of spent ion exchange resins in bitumen is suitable for resins of both low-and intermediate activity level, as stated by Bartholdsson. The drying of the ion exchange resins produces steam and water vapor. Depending on the activity level in the resins, some activity can be transferred to this vapor and this needs to be handled. The condensed vapor is pumped to a special tank if the resins being dried have a higher activity level and to another treatment pathway if the resins have a lower activity level. After the water has evaporated all the waste material is left in the dryer, meaning that this process does not produce any other by-products, according to Bartholdsson.

The areas at the facility where there is radiation present, such as the dryer and mixing area, are screened off and nobody enters these areas. Safety precautions involve keeping a distance to areas where radiation is present and not entering them. The workers at the facility are not subjected to any radiation during normal operation, Bartholdsson reports. The facility uses filtered ventilation where activity is constantly measured and any increase in radiation level would be detected, minimizing the risk of spreading of radioactivity. When it comes to other possible risks that might arise with this treatment method, Bartholdsson mentions that the process involves heat. However, all equipment used is made to withstand high temperatures. Other than that, Bartholdsson views the treatment method as low risk. In instances where there is a need for cleaning out bitumen from the mixing vessel, a substance called perchloroethylene is used. Perchloroethylene is a carcinogenic (Bartholdsson, 2026) and environmentally hazardous chemical (MSB, n.d.). The perchloroethylene is appropriately handled and there is minimal contact with the substance. From a non-radiological perspective there are no other substances hazardous to the environment or health used for the treatment process at the facility. The operative temperatures of the treatment process are below the flashpoint of bitumen and when the final waste product is in storage it is encapsulated in the mold, with no contact with oxygen. Consequently, Bartholdsson sees no or minimal safety risks related to fire hazards.

The price of the bitumen used at Forsmark is 8100 kr/ton, or 8.1 kr per kg (Grönroos, 2026). Bartholdsson notes that the equipment required for the process is not particularly advanced. The treatment process essentially involves heating a slurry and mixing dry resins with bitumen. While equipment that can withstand high temperatures and remain unaffected by radiation are necessary, Bartholdsson does not perceive the treatment method as relying on advanced and high-end technology that would drive up costs. However, the equipment does require frequent maintenance. In particular, the stirrers used in the dryer and for mixing the resin-bitumen mixture need to be replaced or renovated once a year. These stirrers are exposed to significant wear due to heat and activity which causes the material to become porous over time, making regular maintenance necessary. The treatment process requires only one operator monitoring the process and operators work in shifts, ensuring continuous monitoring. Regarding energy consumption, Bartholdsson noted that the primary energy demand comes from heating and drying the resin slurry, while electric motors driving the stirrers account for a small share of the total energy use.

5.3 Immobilization in polymers

5.3.1 Technology overview

Polymers are essentially large molecules made up of smaller chemical units. The immobilization of radioactive waste in polymers is a relatively new treatment method when compared to immobilization in bitumen or cement (IAEA, 1983, p.71). There are several types of polymers that have been used for this purpose but the most commonly investigated and utilized are polyethylene, epoxy resins, polyester resins and urea-formaldehyde (Richard, 2024, p.7). Countries that have used immobilization of ion-exchange resins with different types of polymers include Germany, France, Switzerland and the USA (IAEA, 1983, pp.72-73). Although polymers are not as common of an immobilization material as cement or bitumen, studies to improve process simplicity, product quality and cost effectiveness have been undertaken in several countries (IAEA, 2002, p.77). The price for industrial polymers range from approximately 18 - 36 kr per kg (PlasticPortal, 2026). Polymers can be divided into two main categories; thermosetting polymers and thermoplastic polymers. Thermoplastic polymers melt or soften when exposed to heat. They are typically heated before mixed with the waste. Thermosetting polymers are first in liquid form and then turned into a solid material using heat and/or a catalyst after the waste has been added. Usually, the immobilization of waste in polymers is carried out as a batch process in a drum or container. Organic ion exchange resins are compatible with polymers but inorganic resins are generally not treated with this method as other immobilization matrices are seen as more suitable (IAEA, 2002, p.77).

5.3.2 Treatment processes

Before being immobilized in polymers, ion exchange resins require pretreatment such as dewatering or drying. Otherwise, water in the resins may lead to problems such as inhomogeneities in the final waste product. Resins containing boric acid may also need additional chemical treatment before immobilization (IAEA, 2002, p.78). Other necessary additives, as well as the exact steps in the treatment process, mechanical and chemical stability of the final waste product also vary depending on the type of polymer used (IAEA, 2002, pp.80-81). The quality of the final waste product can also be affected by trace materials in the waste (IAEA, 2002, p.67).

An example of a facility that uses polymer immobilization as a treatment method for ion-exchange resins is the Narora nuclear power plant in India. The system is visualized in Figure 7. At this facility, spent resins are treated in batches. After the resins have been received, they are transferred into a vessel inside a hot cell. The resin slurry is then discharged into a special drum and dewatered. Following dewatering, two equal portions of polyester and a catalyst additive are added to the drum. The drum contents are thoroughly mixed and then allowed to set and cure within the drum. Once curing is complete, the drum is taken to final disposal. All operations at this facility are carried out remotely (IAEA, 2002, p.79).

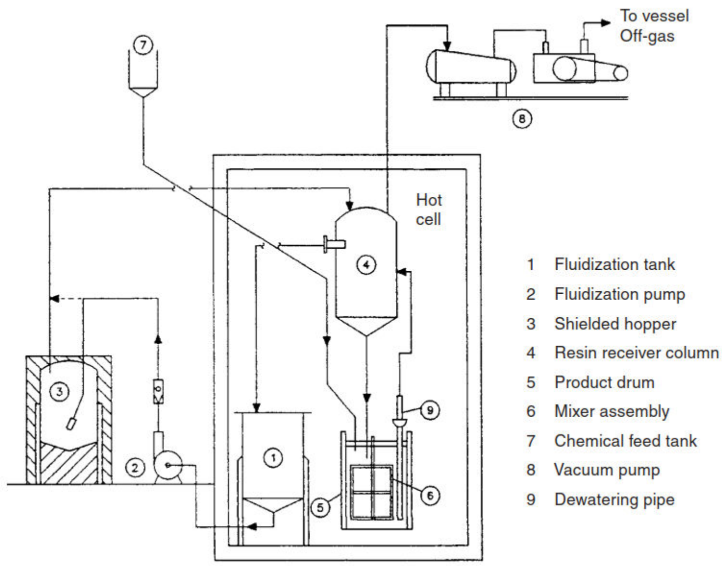

Figure 7. Operational flowsheet of the spent ion exchange resin cementation system used at the waste management plant in Narora, India, (IAEA, 2002)

At the Grenoble Nuclear Research Centre in France a process using epoxy or polyester was developed for immobilizing radioactive waste, including ion-exchange resins. In this process ion-exchange resins are dewatered by using pumps or filtration systems. The resins are then mixed directly with the polymer matrix in 100-l or 200-l drums for about an hour. Polymerization is initiated by adding a catalyst during mixing. The mixing of the additives, ion-exchange resin and the polymer is done at ambient temperatures. After this, the mixture solidifies after 4 to 6 hours. The IAEA describes this process as easy to operate. The only component requiring regular replacement is the blades used for mixing, which are detached and left in the drum every 15-20 uses. Immobilization processes using epoxy present no distinct safety risks, but processes using polyester do due to a substance called monomeric styrene. Monomeric styrene is used to dissolve the polyester during the treatment. Due to its volatility, the presence of monomeric styrene requires explosion-proof equipment and ventilation systems during handling and before polymerization. However, once the mixture has set, no further hazard remains. The facility has a production capacity of 30 l/h (IAEA, 1983, pp. 75-77).

5.3.3 Waste form characteristics

The properties of the final waste form depend on what type of polymer is used to immobilize the ion-exchange resins. When it comes to leaching, polymers perform overall worse than bitumen and cement. But, polymers perform better than cement when it comes to leaching of Cs. Studies have shown that the cumulative leach fraction per cm over 100 days varies between 20-50$\times10^{-3}$ for Cs, 1.3-1.6$\times10^{-3}$ for Co and 1-3$\times 10^{-3}$ for Ce depending on the type of resin (IAEA, 1985, p.52). The compressive strength of the final waste form is between 380-670 kg/cm^2, also depending on the type of polymer. This is higher than for both cement and bitumen. Most polymer waste forms are stable up to 300-450° C, which is higher than bitumen and comparable to cement. The final waste forms are stable up to absorbed radiation doses of 10^5-10^6 Gy, which is lower than both cement and bitumen (IAEA, 1985, p.52). Again, the radiation dose stability depends on the type of polymer. The waste loading capacities that can be achieved with this immobilization method differs between reports. It has been reported to be 50-60% dry resin weight (IAEA, 1985, p.52) but also just 25-50%. These waste loadings are better than cement and comparable to bitumen (IAEA, 2002, p.84). Polymers have also been shown to be resistant to biological degradation and water immersion (IAEA, 2002, p.85).

5.4 Pyrolysis and immobilization in cement

5.4.1 Technology overview

Pyrolysis is a thermal treatment method where waste is heated and broken down in an oxygen-free environment, usually at temperatures between 500°C and 700°C (IAEA, 2002, p.51). In this process, ion exchange resins break down into gases, liquids and solid residue in the form of ash. (Wang and Wan, 2015, p.51) Pyrolysis reduces the overall volume of the waste and the process produces a stable final waste material, a solid pyrolysis ash, that is resistant to biological changes. The pyrolysis process retains nearly all non-volatile radioactive nuclides within the solid residue (IAEA, 2002, p.51) if the treatment temperature is properly controlled (Li and Chen, 2024, p.10).

Pyrolysis can provide a substantial volume reduction of the ion exchange resins and most radionuclides remain bound in the residue. This is highlighted in research as something that could simplify the subsequent stage of immobilization. However, this treatment method generates secondary pollutant gases which require systems for off-gas treatment and gas-cleaning procedures. (Wang and Wan, 2015, p. 51)

5.4.2 Treatment processes

There are two main variants of the pyrolysis process: direct pyrolysis and oxidative pyrolysis. In direct pyrolysis the waste is heated without air supply. After the waste has broken down, the resulting residue is oxidized before further treatment steps such as immobilization. Direct pyrolysis requires additional gas treatment systems in order to manage the emissions produced during oxidation. In oxidative pyrolysis a controlled amount of air is introduced during heating which allows partial combustion of the resins. Studies have shown that oxidative pyrolysis can achieve a higher volume reduction compared to direct pyrolysis. Research has also shown that the overall volume reduction depends on the type of ion-exchange resin, where anionic resins break down more easily than cationic resins (Wang and Wan, 2015, p.51). The possible release of radionuclides is a key concern with pyrolysis of ion-exchange resins (Li and Chen, 2024, p.10). The ability to retain radionuclides such as ^{60}Co, ^{90}Sr and ^{137}Cs in the pyrolysis residue depends on the temperature at which the waste is processed. For cationic resins, results from experiments indicate that at temperatures above 400° C it becomes harder to make sure these elements stay in the solid residue (Wang and Wan, 2015, p.51). Other studies have shown that the retentions of ^{60}Co and ^{90}Sr are above 99.9% when ion-exchange resins are pyrolyzed at temperatures in the range of 750-850° C and the retention of cesium is 99.9% at temperatures below 790° C (Li and Chen, 2024, p.10). The off-gases released during pyrolysis also vary by resin type. Cationic resins have been shown to release gases such as SO_2, CO_2, CO, and water vapor. Anionic resins release trimethylamine, CO_2 and CO (Wang and Wan, 2015, p.51).

A notable industrial application of this treatment method is the THOR process patented by Studsvik. The THOR process has been used at a waste treatment facility in Tennessee where spent ion exchange resins were successfully treated, retaining radioactive and inorganic material in a solid end product (Wang and Wan, 2015, p.51). The feasibility of the pyrolysis treatment method has also been demonstrated in experiments conducted in Japan and Canada (IAEA, 2002, p. 51). An industrial-scale pyrolysis process for ion-exchange resins has been developed by NUKEM Technologies GmbH which can process up to 50 kg/h and where volume reduction factors range from 3 to 10. The resins are pyrolyzed and the off-gases are combusted before being fed through an emission control system with filters (Brähler and Slametschka, 2011, p.1-5).

5.4.3 Waste form characteristics

Residues of ion-exchange resins resulting from treatment processes such as pyrolysis generally require immobilization before their final disposal, according to the IAEA (IAEA, 2002, p. 65). Cement, bitumen and polymers are all suitable immobilization materials for ash but out of these, cement is the most commonly used (IAEA, 2002, p. 66). NUKEM Technologies GmbH describe cementation as a feasible immobilization method for pyrolyzed resins and the project uses in-drum cementation method that reportedly achieves a uniform distribution of the ashes in the cement and provides a final waste product that is mechanically strong and resistant to leaching. Cementation of the ashes leads to lower volume reduction of the final waste form (Brähler and Slametschka, 2011, p.5) since the initial volume reduction achieved by pyrolysis is off-set by the immobilization of the resins in cement.

According to IAEA, resin ash immobilized in cement can offer a more stable final waste form than resins directly immobilized in cement. Resin ash does not swell since the polymeric structure has been destroyed and cannot absorb water, which maintains the mechanical integrity of the final waste form. Resin ash immobilized in cement showed lower leach rates than cement containing untreated resins (IAEA, 1985, pp. 67-69).

5.4.4 The inDRUM pyrolysis process

Studsvik AB has developed and patented inDRUM, a pyrolysis treatment technology for managing low-and intermediate level waste, waste with hazardous properties and other complex waste (Studsvik, 2025). Currently, Studsvik has an inDRUM demonstration facility, inDRUM Demo, but there is ongoing work on developing a commercial full-scale facility, inDRUM Gamma.

The pyrolysis technique itself is not new and Per Lidar considers it a well-proven method. inDRUM is a specific variant of pyrolysis suited for treating waste such as ion-exchange resins and the technology can be used to treat both low-and intermediate activity level resins. Lidar describes the inDRUM pyrolysis process as follows: The waste is contained in sealed drums and heated in a furnace called the Container Treatment Unit (CTU). The CTU is designed to handle 200-liter drums, as this is a common container type among their customers. The inDRUM patented feature is a lance that penetrates the drum lid. This makes the system flexible and allows for control of the environment inside the drum. Through the lance, nitrogen gas, steam or other gases can be introduced. Nitrogen is used to maintain an oxygen-free atmosphere. The gases produced pass through a barrier filter containing ceramic cartridges that capture particles. The system then includes a standard afterburner, or thermal oxidizer, which further combusts the flue gases at high temperatures. This is followed by a quencher-scrubber unit. The quencher cools the flue gases and the scrubber cleans them. After that, the gases pass through a pre-filter and a HEPA filter. Finally, the gases are released through the emission stack located at the far end of the facility. The entire facility is kept under slight negative pressure. After pyrolyzing ion-exchange resins with the inDRUM method, the remaining material is an inert ash (Lidar, 2026).

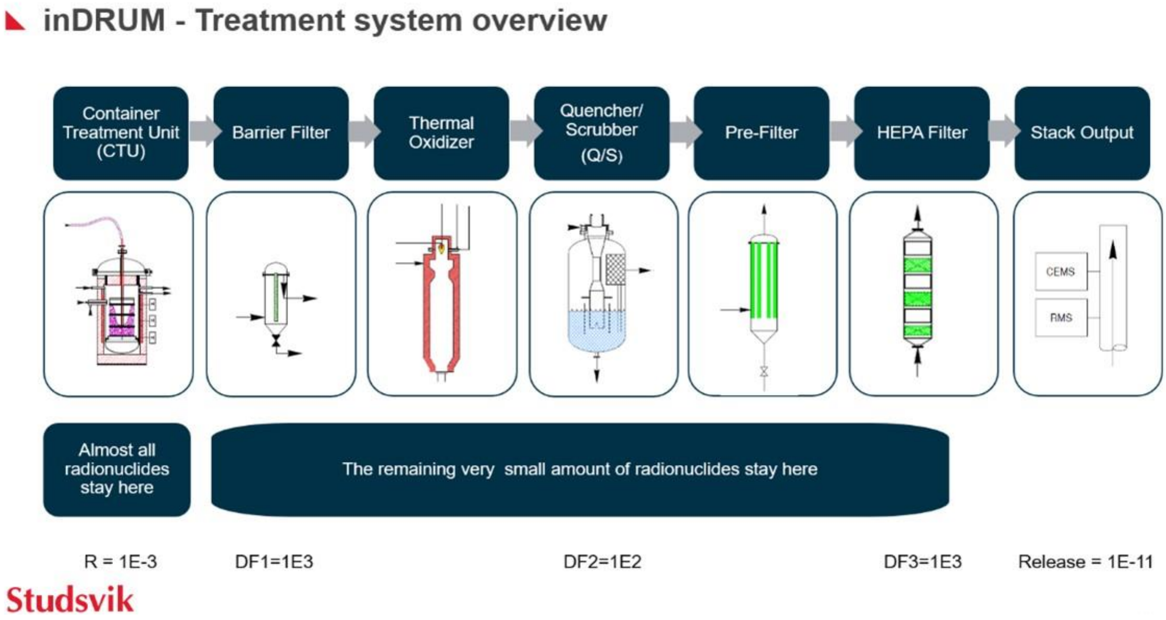

Figure 8. inDRUM system overview, (Karlsson et al., 2025), used with permission.

Some numerical values relating to the inDRUM process can be seen in Figure 8 above. *R* stands for release factor. *DF* stands for decontamination factor. The barrier filter has a decontamination factor of 1000. The scrubber has a decontamination factor of 100 and the HEPA filter has a decontamination factor of 1000. It is estimated that the emissions released through the stack correspond to approximately 10^{-11} of the original amount of non-volatile nuclides present in the waste in the drum, meaning that only an extremely small fraction escapes. Most of the equipment used for this method can be purchased off the shelf. There are suppliers that specialize in manufacturing combustion chambers, scrubbers, filters and similar components, and these are standard products, states Dr. Lidar. Lidar also considers the technology to be easily accessible. The treatment process steps are essentially always the same, but there may be special cases. Some radionuclides are volatile and cannot be contained. If ^{14}C, tritium or iodine are present in the waste these nuclides will leave the drum, and additional measures must be taken to contain them during the treatment process. However, in typical waste from boiling water reactors or pressurized water reactors, these nuclides are not present in significant quantities (Lidar, 2026).

The production rate of treated waste when using the inDRUM technology depends on the size of the drums. At the moment the facility can process one 200-l drum per day. Dr. Lidar notes that there are other pyrolysis facilities capable of treating very large volumes. For example, in the 90's Studsvik built the pyrolysis facility THOR for ion-exchange resins in Erwin, Tennessee. It was designed to treat ion exchange resins from half of the nuclear power plants in the US at the time. Regardless of the resin type, the treatment method results in an ash that forms a stable final product. According to Dr. Lidar this ash could be immobilized in cement. If the ash is immobilized in cement, the waste stability can be improved as cementation reduces the migration of nuclides from the waste matrix. But, there are established procedures agreed upon with SKB that must be followed. Recently, due to issues specifically related to ash, SKB has tightened requirements, meaning that the regulatory demands are increasing (Lidar, 2026).

If operated as intended, the inDRUM method can achieve a volume reduction of up to 95% when pyrolyzing ion-exchange resins. One aspect that needs to be considered in this regard is the increase in dose rate. If all nuclides remain in the drum during the pyrolysis, the dose rate increases by a factor of 20. For example, if the waste has a surface dose rate of 10 mSv/h before treatment, the resulting waste in the drum will have a dose rate of 200 mSv/h after treatment. Spent ion-exchange resins often contain ^{60}Co, ^{137}Cs and ^{90}Sr. By keeping the temperature in the drum below approximately 650° C all nuclides remain within the drum during the pyrolysis (Lidar, 2026).

When asked about secondary waste, Lidar explains that the inDRUM process generated some secondary waste, mainly from the barrier filter. The ceramic filter cartridges also become secondary waste. Regarding emissions, Dr. Lidar notes that the flue gases consist primarily of carbon dioxide and nitrogen oxides, NO_x. The scrubber captures additional components. Sodium hydroxide (NaOH) is added in the scrubber, which binds carbon released from the drum. This can produce sodium carbonate ($NaCO_3$) which is a water-soluble substance that is permitted to be released into the waste-water system in controlled amounts. In terms of radiation protection, Lidar emphasizes that they follow strict regulations. The design for the inDRUM Gamma facility includes shielding from high radiation levels and operations would be remotely controlled. Workers would only be allowed to enter once the waste drums have been removed. When asked whether it is generally an expensive treatment method, Lidar explained that inDRUM's target customers are those whose waste lack cheaper available alternatives. On a per kg basis this pyrolysis process would be more expensive than, say, a combustion treatment, according to Lidar. Considering pyrolysis facilities more generally, Lidar states that operational costs are not particularly high. Running the inDRUM facility requires an operator for the control room and one process operator. Except for the lance and the CTU, equipment used at the inDRUM facility is commercially available. Lidar also notes that maintenance requirements are not unusually high, just routine industrial maintenance is required. Regarding energy use Lidar reports that the process consumes about 1000 kWh per day of operation. Nitrogen gas and propane are also spent during the process (Lidar, 2026).

5.5 Waste form characteristics compared

Table 2 summarizes some characteristics of the different waste forms for easier comparison. For the combined treatment method of pyrolysis and immobilization in cement, several characteristics are not directly comparable and are therefore marked as not applicable.

Table 2. Comparison of waste form characteristics

Characteristic	Immobilization in cement	Immobilization in bitumen	Immobilization in polymers	Pyrolysis and immobilization in cement
Thermal stability	400° C	220°-250° C	300-450° C	N/A
Compressive strength	100-300 kg/cm^2	Will soften under pressure	380-670 kg/cm^2	High
Leaching resistance	High	Moderate	Moderate	Very high
Radiation dose stability	10^8 Gy	10^7 Gy	10^5-10^6 Gy	N/A
Biological resistance	High	Moderate	High	High
Waste loading	10-25%	25-60%	25-60%	N/A

6. Analysis and results

This chapter presents the results of the multi-criteria analysis including the scoring and ranking of the evaluated treatment methods. The final scores are visualized in Table 9. The scoring framework for each criterion can be found in appendix B.

6.1 Scoring against criteria

In the following section, treatment methods are scored against each evaluation criteria. The scoring is illustrated in Tables 3-9. The tables are followed by motivations and explanations for the assigned scores.

6.1.1 Technological maturity and availability

Table 3. Criterion scoring: Technological maturity and availability

Criterion (*i*) & score ($R_{i,j}$)	Technological maturity and availability	1	2	3	4	5
Treatment method (*j*)	Immobilization in cement					X
	Immobilization in bitumen					X
	Immobilization in polymers				X	
	Pyrolysis and immobilization in cement			X		

Immobilization in cement receives a score of 5: The treatment method has been used for immobilization of ion exchange resins for decades at an industrial scale in several countries and is very established. The technology is fully available and developed and needs no adaptation before implementation. Cement is described as readily available by the IAEA.

Immobilization in bitumen receives a score of 5: This treatment method has also been used in many countries for an extended period of time, implying high maturity and availability. According to the IAEA there are many types of bitumen readily available for this purpose.

Immobilization in polymers receives a score of 4: Immobilization in polymers is not as established as cement or bitumen but there has been industrial implementations in several countries. The equipment needed is similar to that used in cementation or bituminization. Studies to improve product quality and process simplicity have been undertaken. While not as established as other methods, immobilization in polymers can be implemented but with some adaptation.

Pyrolysis and immobilization in cement receives a score of 3: Pyrolysis is described as a well-proven and established method in itself. Pyrolysis of resins has been adopted at an industrial scale and its feasibility has been proven further in research. Most, but not all, equipment needed for pyrolysis is readily available. Immobilization of waste in cement is, as mentioned above, a highly mature treatment method. The cementation of pyrolyzed ashes has been described as feasible and cement has been deemed a suitable matrix for this purpose. The combination of pyrolysis and immobilization in cement has been proven, but it has not yet been implemented on a wide scale in industry. Moreover, regulatory demands concerning handling of ashes have been increasing. Overall, this implies that the treatment method requires moderate development or adaptation.

6.1.2 Technical performance

Table 4. Criterion scoring: Technical performance

Criterion (*i*) & score ($R_{i,j}$)	Technical performance	1	2	3	4	5
Treatment method (*j*)	Immobilization in cement			X		
	Immobilization in bitumen				X	
	Immobilization in polymers			X		
	Pyrolysis and immobilization in cement			X		

Immobilization in cement receives a score of 3: Immobilization in cement has a moderate production capacity where the production time is mainly affected by the hardening time of cement. The cement starts to harden relatively fast if the resins do not contain boric acid, but as demonstrated by the Ringhals facility, the molds need to cure for an additional 48 hours before further handling. The Ringhals facility can produce one mold weighing 1600 kg containing 250-300 kg of dry resins per day. Since waste loading is low (10-20%), there is a significant increase in waste volume. Waste loading could be further reduced if the resins contain boric acid. Pretreatment of the resins is not necessary, although recommended in some cases. Some additives are used in the process. Overall, these factors align with a moderate technical performance.

Immobilization in bitumen receives a score of 4: This treatment method requires pretreatment. Before immobilization, resins need to be dried. If the resins are in bead form, they also need to be grinded. No additives are necessary. At Forsmark, the mixing process is not time consuming, but equipment capacity requires multiple process cycles to fill a mold. The Forsmark facility produces around 1-2 molds per week, where one mold weighs 900 with a resin content of 400 kg. The waste loading capacity of bitumen varies between 25–50% and in many cases up to 40–60% depending on resin characteristics, allowing for high waste incorporation. This results in a lower increase in waste volume. This waste loading capacity also allows for a higher waste treatment rate.

Immobilization in polymers receives a score of 3: This method requires pretreatment such as dewatering or drying of the resins. The process often requires additives in the form of catalysts. If the resins contain boric acid, additional additives are required. The exact steps in the process have to be adapted to the polymer type used. The main aspect affecting production time is the solidification of the polymers, which is 4-6 hours at the Grenoble facility. This facility has also shown that the processing rate with this method is 30 l/h and drums containing 100-200 liters can be produced. The waste loading capability of polymers varies between 25-50% and 50-60%. As with bitumen, higher waste loading capability creates the possibility for lower volume increase of the waste and higher waste treatment rate.

Pyrolysis and immobilization in cement receives a score of 3: The main advantage of pyrolysis is the volume reduction of the waste. The inDRUM process achieves a volume reduction of 95% and the technique used by NUKEM Technologies GmbH achieves volume reduction factors ranging from 3-10. This initial volume reduction will however be off-set by the incorporation of the ashes in cement. Production rates vary. The inDRUM process produces one 200-l drum per day and the process used by NUKEM Technologies GmbH has a processing capability of 50 kg/h. Higher production capacity of pyrolysis processes has been demonstrated in industrial applications. This combined treatment method will be affected by the production capability and rates of cementation processes. There is no pretreatment needed before pyrolysis, but pyrolysis systems require nitrogen gas and propane, as well as sodium hydroxide in the quencher. The subsequent cementation may require additives.

6.1.3 Secondary waste generation

Table 5. Criterion scoring: Secondary waste generation

Criterion (i) & score ($R_{i,j}$)	**Secondary waste generation**	**1**	**2**	**3**	**4**	**5**
Treatment method (j)	Immobilization in cement					X
	Immobilization in bitumen				X	
	Immobilization in polymers				X	
	Pyrolysis and immobilization in cement		X			

Immobilization in cement receives a score of 5: Information from the qualitative study shows that this treatment method results in very little or no by-products and there is no secondary radioactive waste generated. At the Ringhals facility, some dust from the cement and lime (calcium carbonate) does occur, but is handled by the ventilation. The mixing blades are left in the waste container and do not need any handling after the treatment process.

Immobilization in bitumen receives a score of 4: The drying process produces steam and vapor that may contain radioactive particles and needs further handling and management. Resins in bead form need to be grinded which could result in some secondary waste. As reported by Bartholdsson, this treatment method does not produce any other by-products.

Immobilization in polymers receives a score of 4: There is no obvious secondary waste generation reported in literature. Like the bituminization process, the resins need to be dried before immobilization in polymers which produces steam and vapor that may need further management. After the treatment process, the mixing blades are reportedly left in the container, further minimizing secondary waste handling.

Pyrolysis and immobilization in cement receives a score of 2: Pyrolysis generates secondary pollutant gases that require significant off-gas treatment and gas-cleaning procedures. Beyond ash, pyrolysis may also produce liquids that need handling. In processes like inDRUM, filters also become secondary waste. The subsequent cementation process produces little to no by-products or secondary waste.

6.1.4 Radiation safety

Table 6. Criterion scoring: Radiation safety

Criterion (*i*) & score ($R_{i,j}$)	Radiation safety	1	2	3	4	5
Treatment method (*j*)	Immobilization in cement					X
	Immobilization in bitumen				X	
	Immobilization in polymers				X	
	Pyrolysis and immobilization in cement			X		

Immobilization in cement receives a score of 5: This process requires mixing which might stir up nuclides if the container is not covered. However, in practice these processes are usually conducted in shielded hot cell facilities and remotely controlled. At Ringhals, untreated resins are covered with water which minimizes risk of radionuclides spreading through the air. No pumps are used in the piping system to minimize radiological risks. The water used for the mixture simultaneously cleans the equipment when added, further minimizing risk of contaminated equipment. This process requires no heating, meaning it produces no vapors or gases where nuclides could be present. There is a small risk of contamination if water collects on top of the molds, but this is monitored. After the lid is cast on the molds at Ringhals, the resulting waste form has no contamination on the outside. During normal operations, there is no exposure to workers.

Immobilization in bitumen receives a score of 4: This treatment process involves both heating and stirring which might mobilize nuclides and generate vapors containing activity. At Forsmark, the exposure risk is mitigated by screening off areas such as the dryer and mixing area. The facility also used filtered ventilation where an increased radiation level would be detected.

Immobilization in polymers receives a score of 4: Stirring during the mixing process may mobilize radionuclides. Heating is also often part of the process, increasing the risk of vapors containing radionuclides. These treatment processes are carried out in hot cell facilities or remotely. The IAEA describes the process as easy to operate and with no distinct radiation hazards.

Pyrolysis and immobilization in cement receives a score of 3: Although the majority of the radionuclides remain in the ash when the temperature of the pyrolysis process are carefully controlled, the method still involves steps where radionuclides can be mobilized. During pyrolysis the resins are broken down, producing off-gases and vapors that can contain radionuclides. These gases are managed by several barriers such as HEPA-filters, thermal oxidation and scrubbers which ensure emissions are extremely low. Despite these controls, the need to manage and filter off-gases means some degree of radionuclide mobilization does occur. In addition the subsequent cementation of the ash requires handling and stirring of the ashes and must be performed with enclosed or shielded environments to prevent spread. As stated in this report, pyrolysis and cementation processes can be carried out remotely or with proper shielding, protecting workers from exposure.

6.1.5 Safety and environment

Table 7. Criterion scoring: Safety and environment

Criterion (i) & score ($R_{i,j}$)	Safety and environment	1	2	3	4	5
Treatment method (j)	Immobilization in cement					X
	Immobilization in bitumen				X	
	Immobilization in polymers				X	
	Pyrolysis and immobilization in cement			X		

Immobilization in cement receives a score of 5: The treatment method requires no heat and can be done at room temperature. At the Ringhals facility, lime is used. Lime is corrosive, although workers do not come into contact with it. Cement and lime do produce some dust. Other than that, the process uses no additional hazardous materials and produces no emissions.

Immobilization in bitumen receives a score of 4: This treatment method requires high temperatures, although they are kept below the flashpoint of bitumen. Bitumen is a combustible material but after being encapsulated in the mold there is no contact with oxygen, lowering the risk of fire hazards. Perchloroethylene is used at Forsmark during maintenance and is a carcinogenic and environmentally hazardous chemical, although it is appropriately handled and there is minimal contact with the substance for workers at Forsmark.

Immobilization in polymers receives a score of 4: This treatment method uses heat in many cases, but not all. If a polyester material is used for immobilization the process requires the use of monomeric styrene. Processes using epoxy material reportedly present no special hazards according to the IAEA.

Pyrolysis and immobilization in cement receives a score of 3: Pyrolysis systems use very high temperatures in the CTU and afterburners. Depending on the type of resin, pyrolysis may produce SO_2, CO_2, CO, vapor and trimethylamine. These emission risks can be mitigated by using off-gas treatment systems and procedures. The sodium hydroxide used in the quencher at the inDRUM facility produces sodium carbonate. This is only released in controlled amounts. The subsequent cementation process does not use any heat and produces no emissions.

6.1.6 Final waste form quality

Table 8. Criterion scoring: Final waste form quality

Criterion (*i*) & score ($R_{i,j}$)	Final waste form quality	1	2	3	4	5
Treatment method (*j*)	Immobilization in cement				X	
	Immobilization in bitumen			X		
	Immobilization in polymers				X	
	Pyrolysis and immobilization in cement					X

Immobilization in cement receives a score of 4: The stability of the final waste form is sensitive to resin composition and boric acid content. The mechanical integrity can be compromised if the resins swell, causing the material to crack. The compressive strength is 100-300 kg/cm^2. Cement is resistant to biological degradation. The final waste form is resistant to temperatures over 400° C and is not flammable. The material is stable up to absorbed radiation doses of 10^8 Gy. Overall, cement has the most favorable leach rates compared to bitumen and polymers.

Immobilization in bitumen receives a score of 3: Bitumen can react with oxidizing materials and is combustible. The mechanical stability of the final waste form depends on the container, since bitumen will soften under pressure and will start to melt at around 220°-250° C. Bitumen is resistant to water, however the integrity of the final waste form is sensitive to swelling of the resins. Bitumen is moderately resistant to biological degradation. The material is stable up to absorbed radiation doses of 10^7 Gy and has moderate leach rates.

Immobilization in polymers receives a score of 4: The final waste form can be affected by moisture or trace materials in the resins. The properties of the waste form also varies depending on the type of polymer used. The compressive strength is 380-670kg/cm^2. Polymers are resistant to temperatures up to 300-450° C and stable up to absorbed radiation doses of 10^5- 10^6 Gy. This material is resistant to water and biological degradation. Polymers have the overall least favorable leach rates compared to bitumen and cement.

Pyrolysis and immobilization in cement receives a score of 5: If all nuclides remain in the ash after pyrolysis, the radiation dose rate of the waste will increase, and this could affect the stability and characteristics of the final waste form. However, the cementation of pyrolyzed ashes is repeatedly described as a favorable method. Pyrolysis of resins produces ash that forms a stable waste product. The stability is further improved by cementation, since the cement reduces migration of nuclides. According to the IAEA resin ash immobilized in cement provides a final waste product that is more stable than resins directly immobilized in cement. Since resin ash does not swell, the mechanical integrity of the final waste form is maintained. Research has also showed that ash immobilized in cement have lower leach rates than untreated resins immobilized in cement. This has further been demonstrated by NUKEM Technologies GmbH who achieves a final waste product that is mechanically strong and resistant to leaching after immobilizing pyrolyzed resins in cement. Since direct immobilization already achieves a score of 4, and this combined method is reported to achieve an even more stable waste product, a score of 5 is assigned.

6.1.7 Economy and resource efficiency

Table 9. Criterion scoring: Economy and resource efficiency

Criterion (*i*) & score ($R_{i,j}$)	Economy and resource efficiency	1	2	3	4	5
Treatment method (*j*)	Immobilization in cement				X	
	Immobilization in bitumen			X		
	Immobilization in polymers			X		
	Pyrolysis and immobilization in cement		X			

Immobilization in cement receives a score of 4: This method uses inexpensive raw materials, as described by the IAEA. The cementation process relies primarily on conventional industrial equipment such as tanks, mixers, transfer pipes and mold which suggests low investment costs. At Ringhals, the molds represent the greatest cost component, but the overall material costs remain modest. Cement itself is inexpensive, although rather large quantities are required with up to 1600 kg used per mold and an additional 300 kg of special concrete for the lids. Based on the material costs from the qualitative study, the material cost is 28 000-30 000 kr/ton resins, excluding the cost of the mold. Operational resource demands and maintenance demands are low, with no major recurring expenses except for the renewal of the cementation line in 2008. Energy use is low, as the treatment method only requires limited electricity for mixing and no heating. Overall, immobilization in cement uses low-cost materials, simple equipment, minimal staffing, low energy consumption and has low maintenance needs.

Immobilization in bitumen receives a score of 3: According to IAEA, bitumen is considered available at a reasonable cost. This treatment method also uses less material per kg resins than immobilization in cement. Based on the qualitative study, the cost of bitumen per treated ton of resins at Forsmark would be 10 125 kr, which is lower than cement. However, this treatment method is more resource intensive due to its dependence on heating. The required equipment varies depending on the technique used, ranging from evaporators, condensers and extruders in continuous processes to mixing equipment and molds in batch processes. This means that the investment cost also varies. While Bartholdsson notes that the equipment used at Forsmark is not unusually advanced, it must be capable of withstanding high temperatures and radiation levels. Maintenance needs are recurrent with stirrers and mixing equipment needing replacement regularly. Staffing needs are low, which contributes to cost efficiency. Even though stirring motors contribute little to energy use, the overall energy demand is increased since heat is used to dry the resins and melt the bitumen. Taken together, the low raw material cost, the reliance on heated processing steps, some specialized equipment and regular equipment maintenance this method has overall good economic and resource efficiency.

Immobilization in polymers receives a score of 3: The price of polymers vary but is approximately 18-36 kr/kg. For a process such as the once used at the Narora plant, this would put the cost of raw material at 18 000-36 000 kr/ton resins. The process requires several additives which contribute to a higher material consumption than simpler methods. Immobilization in polymers often includes drying and in some cases ventilation systems and explosion-proof equipment is needed, which increases total costs. Maintenance needs also contribute to a moderate score. Reports from facilities such as Grenoble indicate that equipment such as mixing blades require regular replacement. The energy consumption varies. Some polymer processes require heating while others do not, resulting in an overall moderate energy consumption. The combination of the amount of different types of additives needed, material costs, specialized equipment requirements and maintenance needs leads to a moderate score.

Pyrolysis and immobilization in cement receives a score of 2: Pyrolysis is inherently a more energy intensive method, since it requires sustained heating at high temperatures. The inDRUM process consumes approximately 1000 kWh per day of operations, in addition to nitrogen gas and propane, contributing to the overall energy and resource costs. Beyond pyrolysis this method also includes immobilization in cement, which demands extensive equipment since the combined method required both a pyrolysis facility followed by a cementation facility. This results in higher investment costs than any other methods assessed. In addition to the operational and energy demands of pyrolysis, the subsequent cementation step introduces further material and production costs. While staffing needs are low for both processes, this is off-set by the combined equipment and energy demands. Maintenance needs are moderate or low for both pyrolysis and cementation but a combination of these inevitable has higher maintenance costs than single-process methods. When considering total energy demand, equipment needs, resource consumption and maintenance requirements, this combined method scores low on economic and resource efficiency.

6.2 Result of multi-criteria analysis

The final scores for each treatment method were calculated according to equation (1).

Table 9. Final scores of treatment methods

Treatment method, j	**Final score**$_j$ = $\Sigma_{i=1}^{7}(W_i R_{i,j})$
Immobilization in cement	117
Immobilization in bitumen	101
Immobilization in polymers	99
Pyrolysis and immobilization in cement	83

The final results of the multi-criteria analysis show that immobilization in cement achieves the highest overall score and is to be considered the Best Available Techniques (BAT) for treatment of organic ion exchange resins from nuclear power plants. Immobilization in cement scores high across key criteria. In particular, it performs well in radiation safety, technological maturity and final waste form quality, which contributes to its top ranking.

Immobilization in bitumen received the second highest score followed by immobilization in polymers. Pyrolysis and immobilization in cement received the lowest score. Given the criteria and weights applied in this study, this result indicates that immobilization in cement represents the most balanced treatment method when considering technical maturity, radiation safety, environmental impact, final waste form quality and economic factors.

Immobilization in bitumen does not receive the highest score despite its high waste loading capacity and lower material cost than cement. Although these aspects contribute positively to technical performance and economy, the treatment method is reliant on processes involving heat, involves a combustible material and requires pretreatment of the resins which increases both energy use and process complexity. The final waste form is sensitive to swelling of the resins and will soften under heat or pressure. Bitumen also has lower radiation dose stability and thermal stability than cement. These factors negatively affect the criteria with the highest weights and outweigh the benefits gained from the high waste loading and material efficiency.

Immobilization in polymers score slightly lower than bitumen. This treatment method can achieve a high waste loading and a final waste product with very good mechanical strength and performs comparably to cement in the final waste form quality criterion. It is, however, a less established method and requires more adaptation, pretreatment and additives. This treatment method may involve heat and hazardous substances which negatively affects the criteria of safety and environment as well as radiation safety. Furthermore, higher material costs and the need for additives results in a lower score for economy and resource efficiency. Secondary waste generation is low, but the combination of limited establishment, lower economy and resource efficiency and lower radiation safety than immobilization in cement gives immobilization in polymers a lower overall score.

The combined treatment method of pyrolysis and immobilization in cement scores lowest. While pyrolysis can offer a great volume reduction of the waste and the subsequent immobilization of the ashes in cement creates a highly stable final waste form, these benefits are off-set by several factors. The performance of this treatment method in the MCA is limited by the energy demand, increased process complexity, secondary waste generation, required off-gas treatment and overall total higher costs. Furthermore, the limited implementation of this combined treatment method in the industry contributes to a low score.

6.3 Results of sensitivity analysis

The sensitivity analysis was conducted by varying the score for the treatment methods in each criterion, $R_{i,j}$, by ±1. The weights, W_i, were also varied by ±1. The varying of scores and weights was done separately. The limits of the scoring and weights (1-5) were not exceeded or undershot. The results are presented in Table 10, with the original final scores in the second column, followed by the effects on the final score when varying the criteria scores and weights.

Table 10. Results of sensitivity analysis

Treatment method, j	**Original score$_j$=$\Sigma_{i=1}^{7}(W_i R_{i,j})$**	**Score ($R_{i,j}$) + 1**	**Score ($R_{i,j}$) - 1**	**Weight (W_i) + 1**	**Weight (W_i) - 1**
Immobilization in cement	117	+10	-26	+22	-31
Immobilization in bitumen	101	+22	-26	+20	-27
Immobilization in polymers	99	+26	-26	+18	-26
Pyrolysis and immobilization in cement	83	+21	-26	+13	-21

The original final scores had a mean value of 100 with a minimum and maximum deviation of ± 17 from this value. Increasing the scores with +1 resulted in variations ranging from +10 to +21, depending on how close the original scores were to the upper limit. Increasing the scores resulted in a change of ranking of the treatment methods, with immobilization in polymers surpassing immobilization in bitumen in the final score. The ranking for immobilization in cement and pyrolysis and immobilization in cement did not change. Decreasing the scores with -1 resulted in a consistent variation of -26 points and the ranking did not change.

Varying the weights resulted in changes between +13 and +22 when increased by 1 and between -21 and -31 when decreased by 1. The ranking of the treatment methods did not change in either case. Immobilization in cement achieved the highest score in every scenario of the sensitivity analysis.

7. Discussion

The results presented in the previous section provide a structured comparison of the treatment methods. However, they depend on the assumptions of the multi-criteria analysis, particularly the chosen criteria, scoring framework and weights. The criteria and weights reflect principles of BAT as well as aspects considered important in the evaluation of treatment methods for radioactive waste. Therefore, criteria related to radiation safety and final waste form quality were assigned the highest weights, followed by safety and environment and technological availability and maturity. Aspects such as secondary waste generation and technical performance were regarded as important, but not critical, and received weights in the mid-level range. Economy and resource efficiency was given the lowest importance. These choices influence the outcome by favoring methods that perform well in highly weighted criteria.

The following sections therefore discuss the identification of immobilization in cement as BAT including its benefits, limitations and the implications of the methodological choices.

7.1 Immobilization in cement as BAT: benefits and limitations

The results indicate that when prioritizing radiological as well as environmental safety, technological maturity and long-term stability, immobilization in cement emerges as the BAT-alternative.

Even though immobilization in cement is identified as BAT in this study, there are limitations associated with the treatment method. The most prominent drawback is the low waste loading capacity. If the resins contain boric acid, this reduces the waste loading even further. Compared to pyrolysis, bitumen and polymers, direct immobilization in cement leads to higher volume increase of the final waste form. This places higher demands on storage, transport and final repository capacity, something that successively becomes of greater importance as the available space at final disposal sites is limited. Another limitation is the sensitivity of the cemented waste form to resin swelling. Ion exchange resins may reabsorb water and swell, leading to the cement cracking which would compromise the waste form's integrity in final repository. While these risks can be mitigated through careful formulation of the cement mix and the use of additives, the treatment method nonetheless requires process control and regular quality assurance.

In addition to its strong performance when it comes to technological availability and maturity, economic viability, radiological-and environmental safety and overall long-term stability, is has also proved a reliable method for producing waste forms that comply with waste acceptance criteria (WAC) for final disposal in Sweden. This has been demonstrated by the waste forms produced at Ringhals. WAC, however, are often site-specific and it may be that this treatment method must be adapted to fulfill WAC at other facilities.

Immobilization in cement is a well-proven and established treatment method that has been used in the industry for decades. While presenting a safe, robust and reliable waste management method, becoming dependent on old treatment techniques such as cementation may become a limitation in the future, if this hinders the transition to safer and more effective treatment methods as they emerge. The results in this thesis support the continued use of immobilization in cement under the current conditions. However, if there are regulatory och economical changes or new treatment methods and technologies are developed, BAT-evaluations must be adapted. This means that while immobilization in cement is identified as BAT today, that may not be the case in the future.

7.2 Methodological limitations and implications

The results in this thesis depend entirely on how the multi-criteria analysis was developed and performed. A multi-criteria analysis is inherently a subjective analysis method and the result is highly affected by the choice of evaluation criteria, the assigned weights as well as the scoring of the treatment methods. The subjective evaluation of what constitutes a high score versus a low score for the evaluation criteria also impacts the final result of the MCA. The overall high score for immobilization in cement is mainly caused by its strong performance in criteria with the highest assigned weights. In particular, technological maturity and availability, radiation safety, safety and environment and final waste form quality. Alternative criteria and scoring framework could have produced a different result.

In this study, criteria relating to safety (radiological as well as non-radiological), technological availability and long-term waste stability were given the highest weights. Criteria relating to secondary waste generation, economic and resource efficiency and technical performance were given lower weights. The treatment methods that scored higher in the criteria with higher weights gained an advantage in the aggregated result. Immobilization in cement performed well overall, but particularly well in most criteria with high weights, contributing to its final score and its identification as BAT. Areas where other treatment methods performed better, such as volume reduction, waste loading and material efficiency were captured under criteria with lower weights. As a result, immobilization in cement received the highest score and emerged as the BAT, even though it was out-performed by other treatment methods in certain aspects.

The results of the sensitivity analysis show that the results indeed are influenced by both the scores and the weights. Variations in scores affect methods differently depending on their initial values. High-scoring methods are bound by the limits of the scale, showing smaller variations than low-scoring methods when increasing the scores by +1. In contrast, variations in weights have a greater impact on already high-scoring methods than on low-scoring methods. However, the ranking of the methods remains mostly the same. Immobilization in polymers performs better than immobilization in bitumen when varying the scores by +1. Immobilization in cement consistently ranks the highest, indicating that the identification of this treatment method as BAT is robust.

7.3 Evaluation limitations

The availability of information for this study has been extensive in some areas and more limited in others. For immobilization in cement and bitumen as well as pyrolysis, there is more relevant information available due to more extensive industrial experience, especially in Sweden. The qualitative study of these methods benefitted from detailed information and data in literature as well as the opportunity of interviewing professionals. These sources provided more comprehensive qualitative material, enabling a more in-depth analysis.

The information concerning immobilization in polymers and the combined method of pyrolysis with subsequent cementation is more limited. No interviews could be conducted with industry professionals about immobilization in polymers. As a result, the evaluation and analysis of these treatment methods rely on a smaller data pool than immobilization in cement and bitumen, something that could increase uncertainty.

Obtaining relevant information regarding economic aspects as well as energy demand also proved a challenge. Publicly available data is scarce for all methods and estimations and comparisons are complicated since cost figures and energy consumption are often site-specific and depend on scale of the facility. Furthermore, information relating to costs and economy is often regarded as sensitive and not easily accessible. Consequently, the criterion about economy and resource efficiency could only be assessed at a general and indicative level. Production rates are also dependent on facility scale and design. The production rates mentioned in this study should therefore be interpreted as examples of implementation of the treatment methods, rather than inherent characteristics of the treatment methods themselves.

This study is also limited to four different treatment methods based on the level of technical maturity, availability of information and time constraints. There are other treatment methods available, though these vary in development level, availability and establishment in the industry. Some examples are hot pressing, incineration and vitrification. However, since other possible treatment methods have been excluded from this report, the results should be regarded as a comparative assessment of a set of realistic BAT candidates, rather than a comprehensive evaluation of all existing or possible treatment methods for ion exchange resins.

It may also be argued that the comparison between pyrolysis followed by cementation and the other treatment methods is uneven, since the former is a combined treatment method and the others are not. However, the purpose of this study was to compare treatment methods as complete solutions. From this perspective, the combined method of pyrolysis and cementation must be evaluated in its entirety. The treatment method does offer clear advantages such as volume reduction and a stable final waste form. But, since it is a multi-step process, its increased process complexity, resource demand and limited implementation results in a lower performance when compared to single-step processes in this manner. This does not imply that pyrolysis combined with cementation is an inferior treatment method in all contexts. The results indicate that while it is a technically promising method, it is less suitable as BAT compared to direct immobilization methods given the criteria and weights used in this particular study.

7.4 Extended discussion: sustainability, robustness and interpretation of results

While immobilization in cement performs well in terms of safety and reliability, the question of its sustainability is more complex. The treatment process itself has a low energy demand, as it does not involve any heating. The treatment process itself also has a minimal environmental impact in terms of emissions. However, from a life-cycle perspective, conventional cement production is associated with carbon dioxide emissions and additional energy use. This highlights how a treatment method that is operationally simple and safe may still have a considerable environmental impact due to the immobilization materials used. Here, the development of more environmentally friendly “green” cement could play an important role in improving the sustainability of immobilization in cement as a treatment method. Further research into how these types of green cement can be incorporated into these treatment processes and what this means for the treatment method a whole would also be an important step in making the process more sustainable. Another limitation in terms of sustainability is the low waste loading of cement, which leads to increased final waste form volumes. This creates additional demands for transport, storage and repository capacity, and can therefore be seen as a drawback from a resource efficiency perspective.

While the results of the MCA and the sensitivity analysis indicate that the identification of immobilization in cement as BAT is robust, this should be understood as reflection the most balanced performance under the selected criteria and weights, rather than overall superiority. Had greater emphasis been placed on volume reduction and the environmental impact of the immobilizing material itself, other methods could have ranked higher.

This again shows that the outcome reflects specific priorities, rather than an objective ranking. It further highlights that the identification of a method as BAT depends on context such as regulations, waste characteristics and process properties. Rather than identifying a single universally "optimal" treatment method, the results suggest that different methods may be preferable under different conditions. Immobilization in cement appears most suitable when safety, maturity and reliability are prioritized, while other methods may be more appropriate when efficiency or volume reduction is of greater importance.

7.5 Further research

There are several areas of interest for further research based on this study. One area is further investigation of other, less established, treatment methods such as plasma incineration, vitrification and processes using wet oxidation. Although these treatment methods vary in their development level, further research, technological advancements, increased operational experience and changes in regulations and evaluation priorities could make them valuable and interesting subjects for future BAT- assessments. In this study, the combined method of pyrolysis and immobilization of cement was investigated. There is a plethora of possible combinations of destructive and non-destructive treatment methods that would be beneficial to evaluate in a BAT-assessment. This could be done in order to find new, promising treatment options or in order to optimize already existing treatment routes for ion exchange resins. Combinations such as incineration and subsequent immobilization in cement or bitumen, incineration and subsequent vitrification or plasma incineration and immobilization in polymers are a few examples.

Another area for further work is the use of alternative weights and an extended sensitivity analysis based on this multi-criteria framework. This would enable a more extensive and detailed analysis of how different priorities and assumptions affect the performance and ranking of the evaluated treatment methods as well as the identification of BAT in this study.

The method of using a multi-criteria analysis in order to identify BAT could also be used to investigate treatment methods for other types of radioactive waste from liquid waste streams such as inorganic ion exchange materials, evaporator concentrate and sludges. It would be especially valuable to investigate whether immobilization in cement is BAT for these types of wastes as well. If immobilization in cement proves to be the most suitable method for other waste from liquid waste streams, this could potentially optimize and simplify waste management by reducing the need for other treatment methods.

Finally, future studies would benefit from more detailed information and data about the economic aspects and energy demands of the treatment methods investigated in this study. Life cycle cost analyses and life cycle assessments would be helpful in capturing the full scope of resource use and costs. This would provide a basis for a more comprehensive and in-depth analysis and comparison between the treatment methods investigated in this study.

As described in section 2.2, hydrogen ions are released during the ion exchange process. It is not clear whether this could under certain conditions be linked to the formation of problematic amounts of hydrogen gas. If hydrogen gas were to form and accumulate, this could potentially cause explosions risks. Clarifying whether such conditions can occur in practice, and to what extent, is therefore something that could be investigated in future studies.

8. Conclusions

The objective of this thesis was to identify best available techniques (BAT) for organic ion exchange resins from nuclear power plants using a multi-criteria analysis. Based on the defined criteria, weights and scoring framework, immobilization in cement received the highest final score in the MCA and was identified as BAT for the treatment of organic ion exchange resins. The results of the multi-criteria analysis also show how the evaluated treatment methods perform under the considered conditions. Immobilization in bitumen ranks second, followed by immobilization in polymers. Pyrolysis and immobilization in cement received the lowest score.

The results show that immobilization in cement demonstrates the overall best performance, especially when aspects such as technological maturity and availability, radiation safety, safety and environment and final waste form quality are prioritized. Immobilization in cement has been used for decades, both in Sweden and internationally and is therefore a well-established and fully available technology. This long operational experience reduces uncertainties related to implementation and long-term performance. The process takes place at ambient temperatures and does not involve hazardous chemicals other than dust from lime. Cement is non-combustible and the treatment method does not pose a fire or explosion risk. The absence of heating, flammable materials and toxic chemicals further reduces hazards. The treatment method produces very little to no secondary waste and causes no direct emissions. Another important factor contributing to this result is its performance in radiation safety. The cementation process requires stirring but no heating. It produces no vapor or off-gases that could spread radionuclides. When carried out in shielded or remotely operated facilities the exposure for workers is minimal. Immobilization in cement also scores high in final waste form quality, especially due to its mechanical stability, radiation dose stability, resistance to heat, biological degradation and low leach rates. The final waste form is, however, sensitive to swelling and boric acid content of the resins.

Although this treatment method has a low waste loading capacity and a higher material cost than bitumen, it still performs well from an economic and resource efficiency perspective due to its low energy consumption, low maintenance requirements, conventional equipment and low staffing needs.

Immobilization in bitumen and polymers present as both technically available and economically viable options, but they achieved lower final scores in the multi-critieria analysis due to weaker performance in criteria with the high weights such as radiation safety, safety and environment and final waste form quality. Pyrolysis and immobilization in cement has the benefits of a very high waste volume reduction and a highly stable final waste form. However, this combined treatment method had the weakest performance in the multi-criteria analysis due to a high process complexity, safety aspects, limited establishment, increased energy and economic demand and secondary waste generation. Even though the treatment methods that were not identified as BAT can offer advantages in certain areas and even out-perform immobilization in cement in some criteria, their benefits were not enough to compensate for their lower performance in other criteria in the multi-criteria analysis.

The results of this thesis also indicate that the identification of BAT for treatment of ion exchange resins is dependent on context and shaped by the evaluation criteria and criteria weights. Under the considered conditions in this study, immobilization of organic ion exchange resins in cement currently provides the most balanced and reliable treatment method.

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Appendix A

Interview guide

- Could you introduce yourself? Where do you work and what is your role?
- How do you treat spent ion exchange resins at the facility where you work? Can you describe the main steps of the treatment process?
- How long have you used this treatment method for ion exchange resins?
- What is the typical production rate? Would you say that it is speedy or time-consuming?
- How sensitive is the process to variations in the ion exchange resins, for example moisture or composition?
- Can the treatment method be used to treat both low-and intermediate-level ion exchange resins?
- How is the total waste volume affected by this treatment method? How great is the increase/ decrease in volume?
- Does the treatment process generate any secondary waste such as off-gases, vapors, by-products or other materials that need further conditioning or handling? If so, how much?
- Is there any radiation exposure for operators during normal operations?
- What measures are taken to protect workers from radiation?
- Are there any procedures that require additional precautions to minimize risk of radiation exposure?
- Is there any risk of spreading or release of radioactivity during the treatment process?
- Are there any occupational hazards related to this treatment process?
- Is there any risk of emission of environmentally hazardous substances during this treatment process? If so, what measures are taken to minimize emissions?
- Is there any risk of emission of substances hazardous to health during this treatment process? If so, what measures are taken to minimize emissions?
- Are there any other safety hazards related to the product or the process?
- How well does the final waste product retain radionuclides? Is there risk of radionuclides escaping from the final product?
- How durable is the final product? Is there risk of the material cracking or degrading over time?
- What are the production costs for this treatment method?
- What are the material costs for this treatment method?
- How many staff are required during normal operations?
- Does the equipment require regular or extensive maintenance?
- Is the treatment method energy intensive? How much energy does it require?
- Are there any practical experiences, advantages or disadvantages related to this treatment method that are important to be aware of?

Appendix B

Scoring framework for evaluation criteria

Criterion: Technological availability and maturity

1. The technology is developed but has not been used in industrial settings. It is not an established treatment method and implementation would require substantial development.

2. The technology has been tested and used in some industrial cases but only to a limited extent. Availability is limited. It could be implemented but requires additional development or adaptation.

3. The technology is mature and has proven functionality but is not widely used across the industry. It can be implemented with moderate adaptation.

4. The technology is well established and regularly used in the industry. It is readily available and implementation requires minimal adaptation.

5. The technology is highly established and widely used throughout the industry. It is fully available and no adaptation is needed.

Criterion: Technical performance

1. The method has poor technical performance. Production capacity and rate is very low. The method leads to significant volume increase of the final waste form. The method typically requires substantial pretreatment or multiple additives.

2. The method has limited technical performance. Production capacity and rate may be slow or variable. Volume increase of the final waste form is considerable. Pretreatment or additives are often required.

3. The method has moderate technical performance. Production capacity and rate is moderate. Volume increase of the final waste form is moderate. Some pretreatment or additives may still be needed.

4. The method performs well technically. Production capacity and rate is high. Volume increase of the final waste form is low. Only minimal pretreatment or use of additives is required.

5. The method shows excellent technical performance. Production capacity and rate is very high. Volume change of the final waste form is minimal or even reduced. The method functions without the need for pretreatment or additives.

Criterion: Secondary waste generation

1. The method generates very large amounts of secondary waste and by-products that require very extensive treatment or handling.

2. The method produces considerable amounts of secondary waste and by-products that require substantial treatment or handling.

3. The method produces moderate amounts of secondary waste and by-products that can be handled with standard treatment systems.

4. The method produces low amounts of secondary waste and by-products that require minimal treatment or handling.

5. The method produces little to no secondary waste and by-products. Handling or treatment of secondary waste or by-products is not needed.

Criterion: Radiation Safety

1. The treatment method has very high radiation risks. Radioactive material is handled or disturbed in ways that exposes operators and there is a significant risk of radionuclide release or spread.

2. The treatment method has high radiation risks. Several steps can cause release of radionuclides, increasing the potential for operator exposure or contamination spread.

3. The treatment method has moderate radiation risks. Some steps may release vapors or residues that contain radionuclides but operator exposure and contamination spread risks are generally manageable.

4. The treatment method has low radiation risks. Radioactive material remains mostly contained during treatment and the potential for operator exposure or radionuclide spread is small.

5. The treatment method has very low radiation risks. Radioactive material remains contained throughout treatment with no potential for operator exposure or radionuclide spread.

Criterion: Safety and environment

1. The treatment method has very high safety or environmental risks. Hazardous chemicals and extreme process conditions are always involved and the process releases environmentally harmful substances. Material-related hazards are significant.

2. The treatment method has high safety or environmental risks. Some steps involve hazardous chemicals or conditions. There is clear potential risk of harmful emissions or material-related hazards unless strictly controlled.

3. The treatment method has moderate safety or environmental risks. Some hazardous materials, heat, or minor emissions occur but risks are manageable with standard safety procedures.

4. The treatment method has low safety or environmental risks. Little hazardous material is used, emissions are minimal, and working conditions are safe under normal operation.

5. The treatment method has very low safety or environmental risks. The process uses little or no hazardous materials, produces no harmful emissions and involves no significant chemical or physical hazards.

Criterion: Final waste form quality

1. The final waste form has very poor quality. It is prone to deterioration, provides weak radionuclide containment and has a high risk of losing integrity under environmental or physical stresses.

2. The final waste form has limited quality. Its ability to remain intact is poor and it may degrade or lose radionuclide containment when exposed to typical environmental or physical stresses.

3. The final waste form has moderate quality. It maintains acceptable integrity under normal conditions but may show weaknesses or partial deterioration under certain conditions.

4. The final waste form has good quality. It remains intact under most environmental and physical stresses and provides reliable containment with low risk of deterioration.

5. The final waste form has excellent quality. It is highly robust under environmental and physical stresses and maintains strong radionuclide containment with minimal risk of degradation.

Criterion: Economy and resource efficiency

1. The method is very resource-intensive and costly. It requires expensive materials, expensive or specialized equipment, high energy consumption, significant staffing and frequent or costly maintenance. Overall economic and resource efficiency is very low.

2. The method has high costs or resource demands. Material, energy, equipment or staffing needs are high, or maintenance requirements lead to increased operating costs. Overall economic and resource efficiency is low.

3. The method has moderate costs and resource use. Material and energy consumption are reasonable, staffing needs are manageable, and maintenance requirements are typical. The need for specialized equipment is not excessive. Overall economic and resource efficiency is moderate.

4. The method is cost-efficient with low to moderate resource requirements. Operating costs, material use, equipment needs, staffing, and maintenance needs are relatively low, making the method economical under normal conditions. Overall economic and resource efficiency is good.

5. The method is highly resource-efficient and economical. Material and energy consumption are low, equipment and staffing needs are very low, and maintenance demands are limited. Overall economic and resource efficiency is very good.