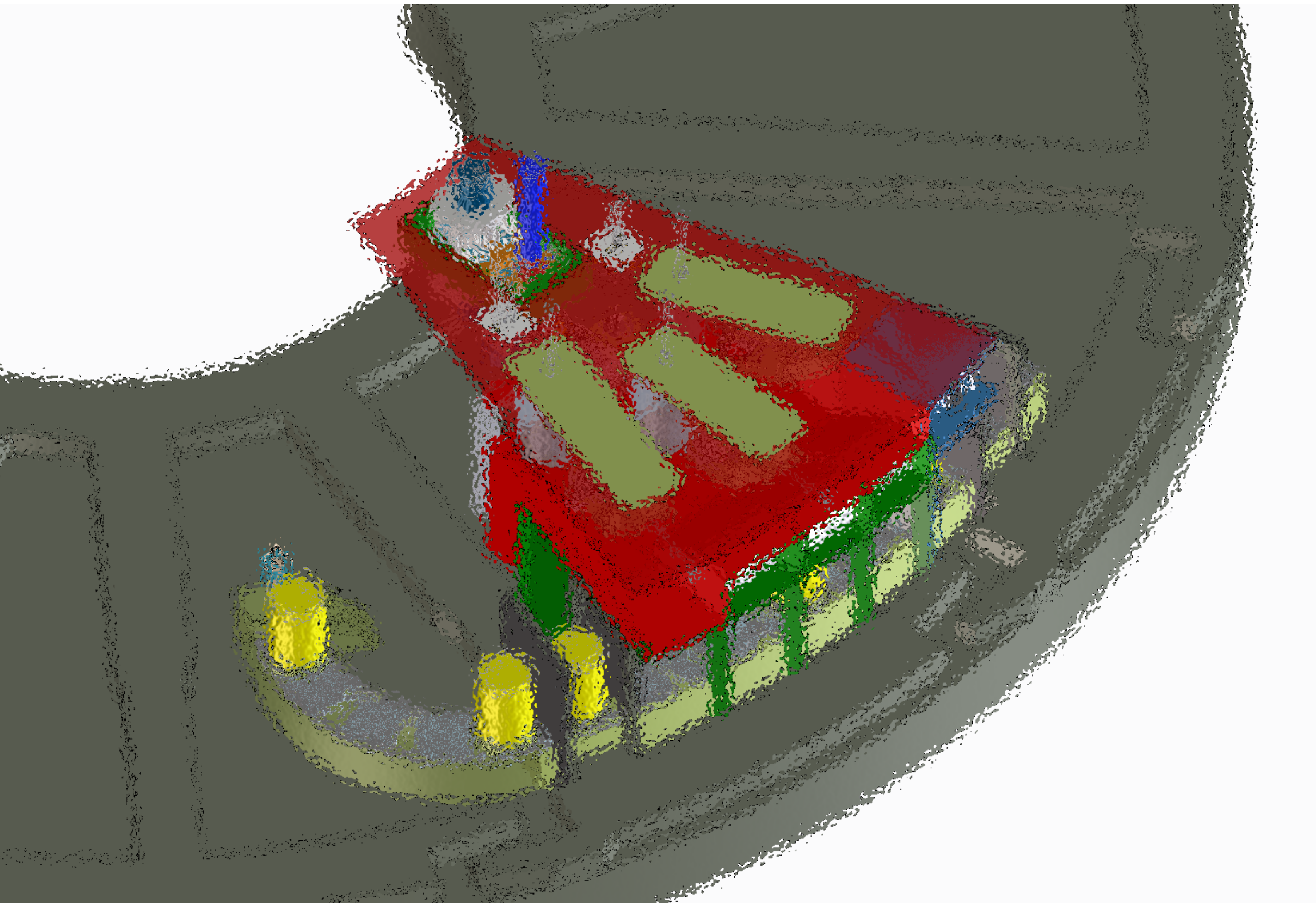

CUTTING TECHNIQUES APPLIED TO DECOMMISSIONING AND THEIR APPLICATION TO THE ESSOR EXPERIMENTAL REACTOR

CASE STUDY

KP-JRC-019

28/10/2025

Foreword

In 2021, the European Commission (EC) adopted a new proposal for a Council Regulation[1] establishing a dedicated financial programme for decommissioning nuclear facilities and managing radioactive waste. This instrument covers the co-funding of the decommissioning programmes of Bulgaria, Slovakia, and the decommissioning of the Joint Research Centre (JRC). A separate Council Regulation[2] was adopted for the decommissioning programme of Lithuania.

The EC JRC is mandated to foster the spread of decommissioning knowledge across all the European Union Member States and facilitate knowledge sharing arising from implementing the above-mentioned decommissioning programmes, funded by the Nuclear Decommissioning Assistance Programme (NDAP).

The decommissioning operators from the NDAP (NDAP Operators) implemented and tested a knowledge management methodology in 2021 through Project ENER/D2/2020-273. Using this methodology, the NDAP Operators can develop Knowledge Products that are currently available to share with other European stakeholders. In addition, this methodology is being implemented by the JRC Nuclear Decommissioning and Waste Management Directorate (NDWMD), which has become a knowledge generator extracting the knowledge from the ongoing decommissioning activities across the JRC´s four different sites (Geel, Ispra, Karlsruhe and Petten.

The JRC´s NDWMD aims to become a Centre of Excellence in nuclear decommissioning knowledge management and to develop a decommissioning knowledge platform which allows exchanging information building on EU best practices through executing the multi-annual financial framework (2021 – 2027) strategy. The operational phase of the project started in 2024 with the objectives to: develop ties and exchanges among EU stakeholders, document explicit knowledge and make it available through multi-lateral knowledge transfers on decommissioning and waste management governance issues, managerial best practices, technological challenges, and decommissioning processes at both operational and organisational level, as well as to develop potential EU synergies.

This is a Knowledge Product prepared by JRC for the JRC NDWMD.

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[1] Council Regulation (Euratom) 2021/100 of 25 January 2021 establishing a dedicated financial programme for the decommissioning of nuclear facilities and the management of radioactive waste, and repealing Regulation (Euratom) No 1368/2013

[2] Council Regulation (EU) 2021/101 of 25 January 2021 establishing the nuclear decommissioning assistance programme of the Ignalina nuclear power plant in Lithuania and repealing Regulation (EU) No 1369/2013

PRODUCT DESCRIPTION

This report, titled "CUTTING TECHNIQUES APPLIED TO DECOMMISSIONING AND THEIR APPLICATION TO THE ESSOR EXPERIMENTAL REACTOR," provides a comprehensive compilation of knowledge on the cutting methods and technologies most commonly employed in the nuclear industry for the segmentation of reactor internal components. It includes a comparative analysis of available technologies and describes the methodological process followed to select the most suitable cutting technique, taking into account technical, operational, radiological, and safety criteria.

In addition, the report presents the engineering solution developed for dismantling the ESSOR reactor internals, which is currently in the design phase. This solution is compared with similar cutting systems used in other nuclear decommissioning projects, highlighting functional differences, limitations, and relative advantages.

The document identifies key factors influencing technology selection, provides decision-making criteria based on real-world experience, and establishes recommendations applicable to complex scenarios involving highly activated components. Prepared by the Nuclear Decommissioning and Waste Management Directorate (NDWMD) at the Joint Research Centre (JRC) in Ispra, Italy, its purpose is to transfer practical knowledge and technical guidance to Member States, supporting the safe and efficient execution of decommissioning operations.

ABSTRACT

The dismantling of nuclear facilities requires precise cutting strategies for components that have undergone prolonged irradiation, material hardening, and exhibit complex geometries in confined or submerged spaces. This case describes the comparative analysis of mechanical, thermal, and hydraulic methods, as well as the technical keys and lessons learned during the design of the cutting system for the ESSOR reactor internals. The approach prioritized radiological safety, operational efficiency, and the protection of adjacent structures, integrating remote handling and containment solutions to minimize personnel exposure and ensure robust control of secondary waste generation.

OBJECTIVE

To establish a comprehensive technical framework for planning and executing the cutting and segmentation of reactor internals. This objective includes defining technology selection criteria based on radiological inventory, metallurgical properties of the components, and geometric and accessibility constraints, ensuring safe and repeatable operations in compliance with ALARA principles.

The report outlines the methodological process followed to determine the most suitable cutting technology, analysing technical, radiological, and operational factors. Furthermore, it provides a comparative assessment between the solution ultimately designed—a dedicated cutting machine for the ESSOR reactor—and other similar machines employed in previous nuclear industry projects, highlighting differences in design, capabilities, and limitations.

The document presents the engineering rationale supporting the selection of this solution, offering practical criteria and lessons learned applicable to complex decommissioning scenarios.

APPROACH

The document adopts a dual perspective combining theoretical analysis and practical application. First, it presents a systematic review of cutting and segmentation techniques currently employed in nuclear decommissioning, including mechanical, thermal, and hydraulic methods. This review establishes technology selection criteria based on radiological inventory, metallurgical properties of reactor internals, and geometric and accessibility constraints, ensuring compliance with ALARA principles and operational safety. In addition, the methodological process for determining the most suitable cutting technology according to these criteria is described.

Second, the report incorporates lessons learned from real-world projects, with particular emphasis on the dismantling of the ESSOR experimental reactor. It analyses the engineering rationale behind the conceptual design of the dedicated cutting machine highlighting critical factors such as remote handling, containment strategies, and secondary waste management. Furthermore, the proposed solution is compared with similar cutting systems deployed in other nuclear industry projects, assessing advantages, limitations, and optimization aspects.

By integrating case studies and practical configurations, the approach aims to bridge the gap between conceptual planning and field execution, providing Member States with technical insights, decision-making criteria, and tools to address complex decommissioning scenarios.

RESULTS, FINDINGS, AND INSIGHTS

The analysis of available cutting technologies and their applicability to the ESSOR reactor demonstrated that mechanical cutting—specifically hydraulic shear technology—offers the most suitable balance between safety, operational efficiency, and waste minimisation. The assessment confirmed that the technology selection process must account not only for technical feasibility but also for radiological constraints, logistics, and environmental considerations.

The practical experience gained during system development reinforced the value of integrating cutting, handling, and waste management into a single automated workflow, ensuring radiological containment and reducing manual intervention. Additionally, the comparison with other decommissioning cases highlighted the importance of adapting solutions to reactor-specific configurations rather than replicating previously applied strategies.

TARGET USERS

Decommissioning program managers, engineering leaders, radiological protection specialists, and operational teams responsible for planning and executing decommissioning.

APPLICATION, VALUE AND USE

This report serves as a practical reference for organizations involved in nuclear decommissioning, particularly those facing the challenge of segmenting highly activated reactor internals. Its application spans the planning, design, and execution phases of dismantling operations, offering structured criteria for technology selection based on radiological, metallurgical, and geometric constraints.

The value of the document lies in its dual approach: combining a comparative review of cutting techniques (mechanical, thermal, and hydraulic) with lessons learned from real-world implementations. By analysing proven setups and case studies, including the ESSOR reactor dismantling project, it provides actionable insights into engineering decisions, remote handling strategies, and containment solutions that minimize exposure and secondary waste generation.

Member States and technical teams can use this resource to benchmark available technologies, understand the rationale behind specific design choices, and adopt best practices for safe, efficient, and ALARA-compliant operations. Ultimately, the report supports informed decision-making and risk mitigation in complex decommissioning scenarios.

EXECUTIVE SUMMARY

This report consolidates current knowledge on cutting and segmentation techniques used in nuclear decommissioning and applies that body of practice to the dismantling of the ESSOR experimental reactor's internal components at the JRC Ispra site. It sets the strategic context in the European Union's decommissioning framework, clarifies the objectives under ALARA and operational safety principles, and translates them into technology-selection guidance for highly activated, geometrically complex components located in constrained environments.

The analysis surveys hydraulic, thermal, and mechanical cutting families and distils their respective advantages, limitations, and waste implications when deployed in-air or underwater. Emphasis is placed on reliability under remote handling, containment of contaminants, compatibility with reactor-specific geometries and materials, and the holistic impact on dose uptake, secondary waste generation, and logistics. This technical landscape establishes the baseline against which ESSOR's solution space is evaluated.

To move from options to decision, the design team applied a structured multi-criteria methodology that weights safety, reliability, performance, complexity, skills, liquid use, waste volumes, and radiological dose. The outcome of that assessment identifies hydraulic shear cutting as the most suitable primary technique for ESSOR, balancing operational robustness with minimal aerosol or liquid secondary waste and offering repeatable, remotely managed operations within the plant's constraints.

Building on that decision, the report presents an integrated, fully remote concept that links cutting, handling, characterization, and packaging into a single contained workflow. The design (currently in the engineering phase) organizes operations across three rooms with sealed interfaces, uses a rotary basket to manage and route segmented pieces, enables in-situ radiological characterization and segregation, and automates loading into shielded or unshielded casks to maintain containment while streamlining throughput and traceability.

Comparative evidence from projects such as Ågesta, Forsmark, BR3, and Măgurele underscores the need to tailor solutions to reactor-specific boundary conditions rather than replicate prior approaches. While Ågesta demonstrates an effective but simpler integrated line for relatively uniform components, ESSOR's greater geometric diversity and radiological heterogeneity necessitate on-line measurement and multi-stream segregation. Conversely, mobile underwater shears and largely manual campaigns that were adequate elsewhere are shown to be impractical for ESSOR's channel-type configuration and performance goals.

Implementation planning highlights clear benefits and known risks. The projected advantages include reductions in collective dose, improved schedule predictability through automation, and significant mitigation of liquid and airborne secondary waste. Principal challenges involve engineering for high variability in parts and access paths, ensuring fault-tolerant remote operations where hands-on intervention is restricted, managing tight space and logistics, and validating radiological assumptions progressively as the campaign advances. The report captures these constraints and codifies lessons that strengthen design assurance and operational readiness.

Overall, the report delivers actionable guidance for ESSOR and a reusable decision framework for similar research-reactor dismantling scenarios. By combining a rigorous technology review with a transparent selection process and an end-to-end solution architecture, it supports Member States and project stakeholders in making choices that are defensible on safety, efficient in practice, and economical in waste management, while advancing JRC's role as a knowledge hub for decommissioning excellence.

KEYWORDS

Cutting strategy; reactor internals; segmentation; nuclear decommissioning; mechanical, thermal; electrochemical; techniques; technology selection; ESSOR; remote handling; radiological safety; ALARA; complex geometries; activated alloys; laser

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ACRONYMS

AWJC	Abrasive Water Jet Cutting
AWSJ	Abrasive Water Suspension Jet
CAMC	Contact Arc Metal Cutting
EIA	Environmental Impact Assessment
EU	European Union
ISF	Interim Storage Facility
JRC	Joint Research Centre (of the European Commission)
LLW/VLLW	Low Level/Very Low Level Waste
MDM	Metal Disintegration Machining
NDWM	Nuclear Decommissioning and Waste Management
PAC	Plasma Arc Cutting
RPV	Reactor Pressure Vessel
RVI	Reactor Vessel Internals

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1. BACKGROUND

1.1. Introduction

The cutting and segmentation of the internal components of a nuclear reactor represent one of the greatest technical challenges in decommissioning operations. These elements, which form the core of the reactor, have been exposed for years to intense neutron and thermal fluxes, resulting in high radiological activation, material hardening, and the presence of complex and hard-to-access geometries. Their handling and sectioning therefore require a carefully planned approach that ensures radiological safety, operational efficiency, and the integrity of adjacent structures.

Among the main challenges associated with these tasks are the high radiological activity and the presence of activated materials, which necessitate the use of remote and highly specialized systems to minimize personnel exposure. Added to this are the difficulties arising from the use of uncommon alloys—such as high-strength stainless steels or nickel and zirconium alloys—which exhibit mechanical and metallurgical behaviour that complicates conventional machining or cutting. Furthermore, the intricate geometry of the internal components, along with their location in confined or submerged spaces, requires the development of tailored solutions for each case, both from a technological and operational standpoint.

Figure 1. Thermal cutting at HDR in Germany **[1]**

This report presents an analysis of the main cutting techniques applied to the internal components of nuclear reactors, covering mechanical, thermal, and hydraulic methods. It also details the cutting-technology selection process and delves into the technical keys and lessons learned during the design of the cutting system for the internals of the ESSOR reactor, developed within the framework of the Joint Research Centre (JRC) activities.

1.2. Main Cutting Technologies

The purpose of this chapter is to provide an overview of the main technologies used for cutting and segmenting the internal components of nuclear reactors. Throughout the section, the most representative techniques in this field are described and discussed. A comparative table is included at the end of the chapter to clearly highlight the differences among these methods, followed by a brief commentary on the key findings and observations.

The dismantling of irradiated components and other highly radioactive structures requires cutting technologies with a level of reliability, robustness, and precision far beyond that demanded by conventional industrial operations. Extreme environmental conditions, the need for remote operation, and the complex geometries of the reactor internals make the selection of the cutting method a critical aspect of planning. Additionally, the process must aim to minimize the generation of secondary waste, a factor that directly affects radiological safety and the subsequent decontamination of the work area.

Cutting technologies commonly employed in nuclear environments can be broadly divided into three main categories: thermal, mechanical, and hydraulic, each offering specific advantages and limitations.

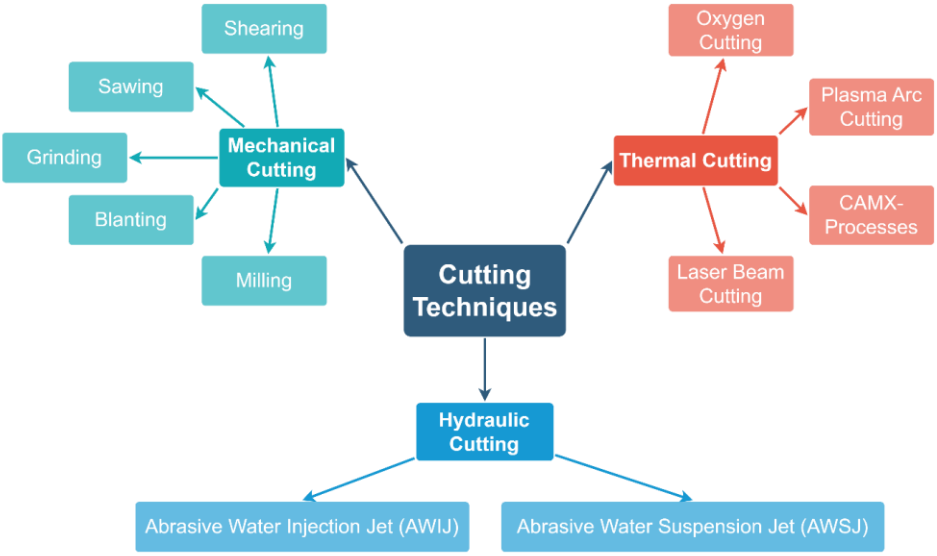


Figure 2. State of the art in cutting techniques

THERMAL CUTTING TECHNIQUES

Thermal cutting methods rely on the application of intense heat energy to melt or vaporize the material without direct contact. Depending on the energy source, three main types can be distinguished:

- Chemical cutting, such as oxyfuel cutting
- Electrical cutting, which includes plasma and metal arc cutting processes
- And laser beam cutting, known for its high precision

These techniques are primarily used for ferrous metals — such as sheets, plates, pipes, or forged components — and can be performed either in air or underwater, depending on the radiological conditions. Thermal cutting processes are well suited for automation and remote handling, although manual applications are also common during specific dismantling operations.

MECHANICAL CUTTING TECHNIQUES

Mechanical cutting, on the other hand, separates materials through direct tool contact, which distinguishes it from thermal processes. Typical methods include shearing, sawing, grinding, milling, and shot blasting. Mechanical cutting generally provides good process stability and accuracy but tends to be slower and more maintenance-intensive than plasma or water jet cutting. Within the nuclear field, specialized equipment such as underwater circular and band saws has been developed to handle thick, massive, and highly irradiated structures. However, the frequent replacement of blades and the associated operational costs remain significant drawbacks.

HYDRAULIC CUTTING

Finally, **hydraulic cutting** encompasses methods that employ high-pressure fluid jets to separate materials without physical contact. This approach allows for highly precise and versatile cuts while generating minimal heat, making it particularly suitable for confined areas and delicate components. Variants that use abrasives — such as Abrasive Water Injection Jet (AWIJ) and Abrasive Water Suspension Jet (AWSJ) systems — have proven highly effective in the dismantling of nuclear installations, enabling controlled cuts with reduced radiological impact.

The document describes the three main categories of cutting technologies. The scope of the analysis will be limited to the preferred methodologies for cutting internal components. Grinding and shot blasting techniques are not included, as these are rarely used for this specific purpose.

Remote handling will play a crucial role in a decommissioning project. Once operations begin, it will be impossible to make changes, conduct inspections, or repair any components in activated areas—except through remote manipulation. Therefore, highly reliable and robust remote handling techniques will be essential for managing and replacing components. The reliability of these systems will also influence the selection of technologies during the main phases of the project.

As previously mentioned, each cutting technique has its own advantages and limitations, which must be carefully weighed and assessed before determining the most suitable option. The most appropriate technology can be selected by considering factors such as cutting efficiency, economic feasibility, and the cutting environment. Additionally, **ALARA principles**, waste management, and the projected reliability and maintainability of the equipment must be considered. Based on experience, the selection of the appropriate cutting technology is typically guided by the following criteria:

- Occupational safety and optimization for radiation protection
- Minimization of secondary waste
- Process safety and operational simplicity
- Reliability and maintainability
- Cutting capability

Below are some examples of cutting techniques that have been used in previous decommissioning projects for segmenting internal components.

Table 1: Cutting techniques used in decommissioning projects

Plant, Country	Reactor type	Project years	Cutting technique
Three Mile Island 2, USA	PWR	1986–1989	PAC
Fort St. Vrain, USA	GCR	1990–1992	PAC
Shoreham, USA	BWR	1991–1993	PAC
Yankee Rowe, USA	PWR	1992–1994	PAC
Trojan, USA	PWR	1995–1996	AWJC
Connecticut Yankee, USA	PWR	1999–2002	AWJC
San Onofre 1, USA	PWR	2001–2002	AWJC
Big Rock Point, USA	BWR	2002–2003	MDM
Grand Gulf, USA	PWR	2011–2012	Mechanical Cutting
Fukushima Daiichi 2, Japan	BWR	1999	Mechanical Cutting
Karlsruhe, Germany	Sodium	2001–2005	Mechanical Cutting
Forsmark 1, 2, 3, Sweden	BWR	2000–2012	Mechanical Cutting
Oskarshamn 1, 2, Sweden	BWR	2003–2013	Mechanical Cutting
Olkiluoto 1, 2, Finland	BWR	2004–2012	Mechanical Cutting
BCOT, France	PWR	2010–2012	Mechanical Cutting
Chooz A, France	PWR	2010–2016	Mechanical Cutting
Zorita, Spain	PWR	2010–2012	Mechanical Cutting

1.3. Hydraulic Cutting Technologies

ABRASIVE WATER JET CUTTING

Abrasive Water Jet Cutting is an advanced technology that uses a high-pressure stream of water mixed with fine abrasive particles to cut materials through erosion. This technique, which can also be applied to industrial cleaning, has become a key tool in machining materials that are difficult to process using conventional methods. It was first patented in the United States in 1968, although its rapid development began in the 1980s. Today, it is a constantly evolving technology, widely used in sectors such as automotive, aerospace, civil engineering, environmental technology, chemical industry, and industrial maintenance.

The process works through a pump that drives water at pressures ranging from 276 MPa to 689 MPa. As it passes through a special nozzle, suction is generated that introduces the abrasive, typically aluminium oxide grains (synthetic corundum), into the mixing chamber. This mixture is stabilized in a final nozzle, forming a hydro-abrasive jet capable of cutting even the toughest materials. The jet produces a very narrow cutting groove, allowing for high-precision cuts in complex shapes, fine tabs, and intricate structures. In metals, tolerances of up to ±0.1 mm can be achieved.

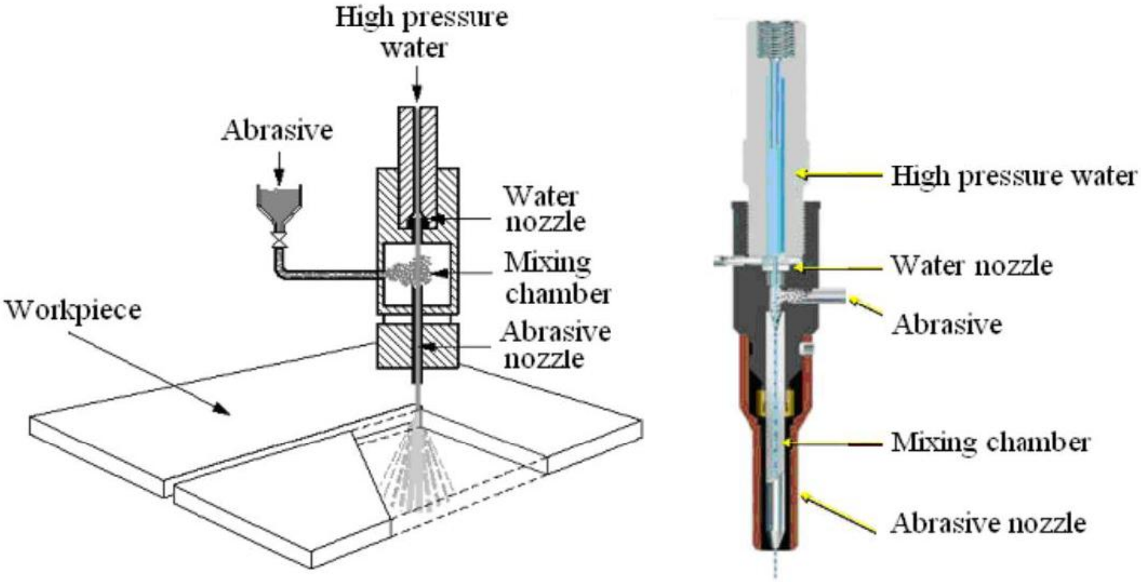


Figure 3: Abrasive water jet cutting **[2]**

This method is especially effective for cutting both metallic and non-metallic materials, including very thick sections, highly reflective surfaces, materials with high thermal conductivity, laminates, composites, and hard synthetics. For example, it can cut stainless steel up to 100 mm thick, aluminium up to 120 mm, stone up to 140 mm, and glass up to 100 mm. However, these values are not strict limits, as virtually any material can be processed with this technique.

Among its main advantages is the absence of thermal stress, since the process is carried out at room temperature, avoiding heat-affected zones and structural alterations. Additionally, the cut surfaces have a smooth finish, similar to fine sandblasting, and heavy burrs are not generated, reducing the need for post-processing. Its versatility allows for cutting both hardened metals and materials with low melting points, making it an ideal solution for demanding industrial applications.

Abrasive water jet cutting systems vary in size, from compact equipment to large-scale industrial installations, with work areas ranging from a few square feet to hundreds. The most technically accurate designation for this technology is "hydro-abrasive treatment" or "abrasive water jet cutting," and it represents one of the most efficient and clean alternatives among non-conventional cutting techniques.

EXPERIENCE IN NUCLEAR POWER PLANTS

In nuclear engineering, the principle of incorporating multiple, redundant, and independent safety layers to prevent a single point of failure is known as "defence in depth".

This approach ensures that even the determination of cutting parameters can contribute to overall job safety. When using Abrasive Water Jet Cutting (AWJC), the jet retains significant power beyond the kerf. Consequently, any object located behind the kerf within the jet's range may be unintentionally damaged.

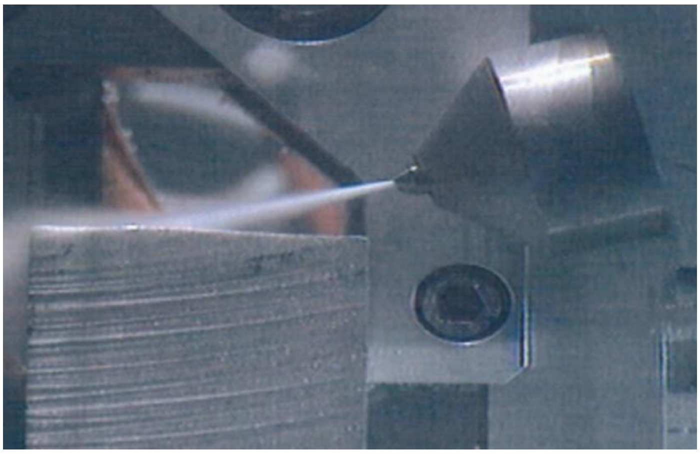


Figure 4. Water jet cutting used in nuclear dismantling **[2]**

An illustrative example from the Versuchsatomkraftwerk Kahl (VAK) plant in Karlstein, Germany, is provided below. The Thermal Shield, a cylindrical component of the reactor pressure vessel internals, featured a wall thickness of 32 mm, with an outer diameter of 2390 mm and an inner diameter of 2438 mm for the RPV itself. This configuration resulted in a narrow gap of only 24 mm.

Figure 5 shows a top view of this geometric arrangement, including the head of a suction device. The Thermal Shield should be cut using AWJC to ensure precision and safety.

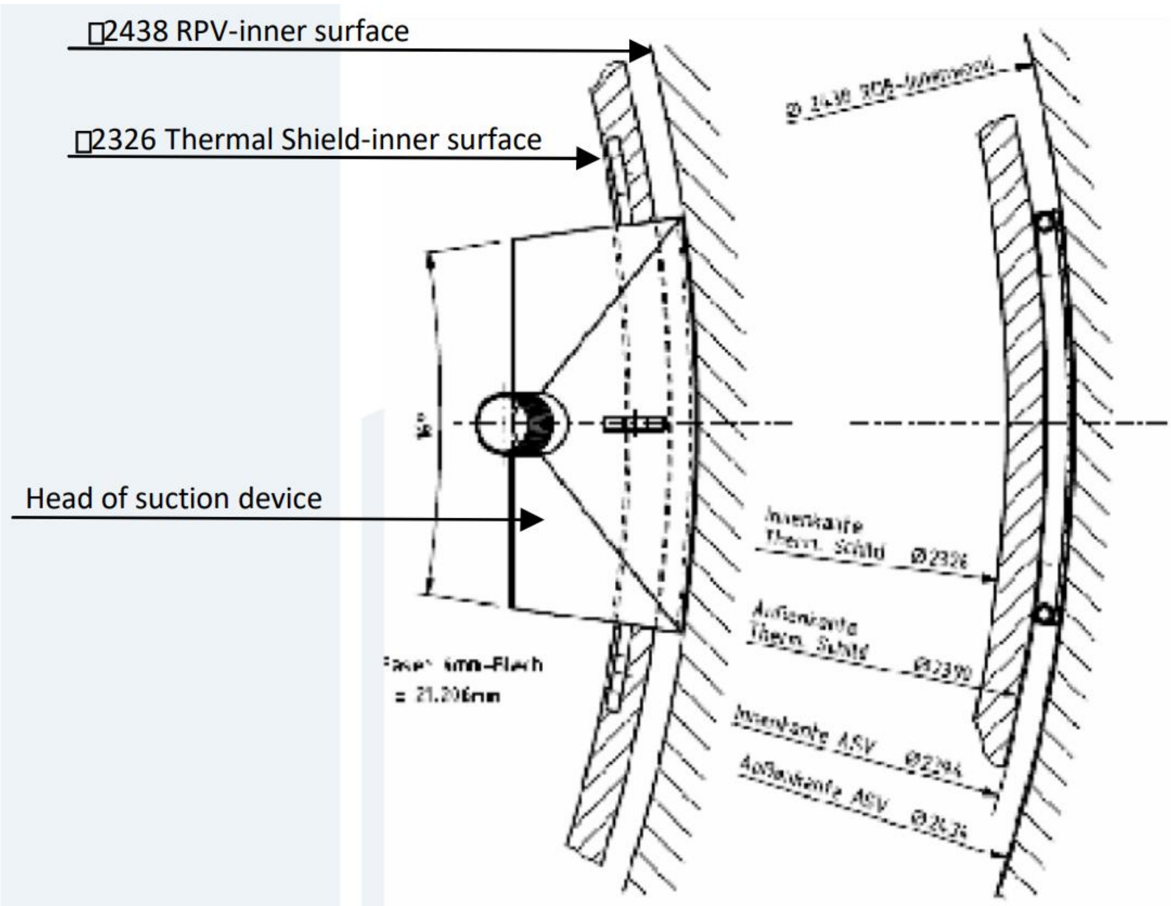


Figure 5: Geometry of Thermal Shield **[2]**

A penetration in the stainless-steel cladding on the inner surface of the RPV was considered a "critical point of failure". Since there was no space to move the thermal shield, a solution was needed to protect the cladding.

Two measures were applied: first, cutting parameters (speed, pressure, abrasive flow, and angle) were optimized so the cladding would not be penetrated during normal operation. Second, a ceramic layer was installed between the RPV and the thermal shield, highly resistant to the water jet and compatible with the cleaning system, requiring no extra handling.

This approach marked an initial step toward "defence in depth" for reactor dismantling. Studies showed that water and abrasive particles remain in the work area and can be collected and disposed of in standard nuclear waste casks.

Abrasive waterjet cutting produces splashes and contamination with hydrosols and aerosols in air and underwater. Underwater, these particles are contained, so systems must be in place to recover and recycle the abrasive. Behind the cut, the jet remains powerful enough to damage other materials, which must be considered in the cutting strategy.

AWJC has also been used for the segmentation of the Rancho Seco reactor vessel (see Rancho Seco Reactor Vessel Segmentation Experience Report, EPRI 2008) and for the Main Yankee reactor vessel internals (see Main Yankee Decommissioning Experience Report, 1997–2004).

One key lesson learned is that combining a highly engineered robotic manipulator with abrasive water jet cutting is very effective for achieving the required precision in vessel cutting projects.

Special attention must be given to the disposal of garnet waste because the cutting process produces a large amount of fragmented garnet. This occurs when thick-walled pieces (9–11 inches or 22.9–27.9 cm) are cut, resulting in significant size reduction. At Main Yankee, the most challenging part of the internals segmentation process was removing the colloidal suspension created by garnet fragmentation during cutting. Additionally, a new licensed waste cask has been developed for storing high-level activity swarf.

The AWJC process was also used at SONGS 1 in San Onofre, California, USA. It was observed that abrasive water jet cutting creates a very narrow kerf (less than 1 mm wide), which allows only a minimal amount of activated metal to be released during cutting. Its ability to cut in multiple directions makes AWJC highly versatile for segmenting complex geometries and areas with limited access. However, this process involves high costs for process control and disposal of highly irradiated secondary waste (see Reactor Vessel Internals Segmentation Experience using Mechanical Cutting Tools – Technological Engineering, Volume X, Issue 2/2013 – ISSN 1336-5967).

1.4. Thermal Cutting Technologies

1.4.1. Plasma arc cutting (PAC)

Plasma cutting is a thermal process used to cut steel and other metals of varying thicknesses. It works by generating a concentrated plasma arc—a high-energy ionized gas stream—between a tungsten electrode and the workpiece. This arc melts the material and removes it with a high-speed plasma jet. Plasma cutting can handle thicknesses up to 150 mm, making it suitable for heavy-duty dismantling tasks.

The unique properties of plasma allow the arc to penetrate thick materials with minimal resistance. However, the high temperature of the plasma arc can have a destructive effect on the surrounding material, which must be considered during planning.

For underwater cutting, maintaining a stable plasma arc for as long as possible is critical. The design of the torch nozzle and the performance of the power source significantly influence cutting efficiency. Standard power sources typically provide up to 600 amps (250 volts) for atmospheric cutting and around 100 mm depth underwater. Combining multiple sources can deliver up to 900 amps (280 volts) for deep underwater cuts.

During cutting operations, dust and aerosols are generated, with particle sizes typically ranging from 0.085 µm to 0.35 µm in air and underwater. Underwater cutting generates secondary waste consisting of approximately 0.03% aerosols, 0.5% hydrosols, and about 99.2% sediments. Both air and water filtration systems must account for these factors.

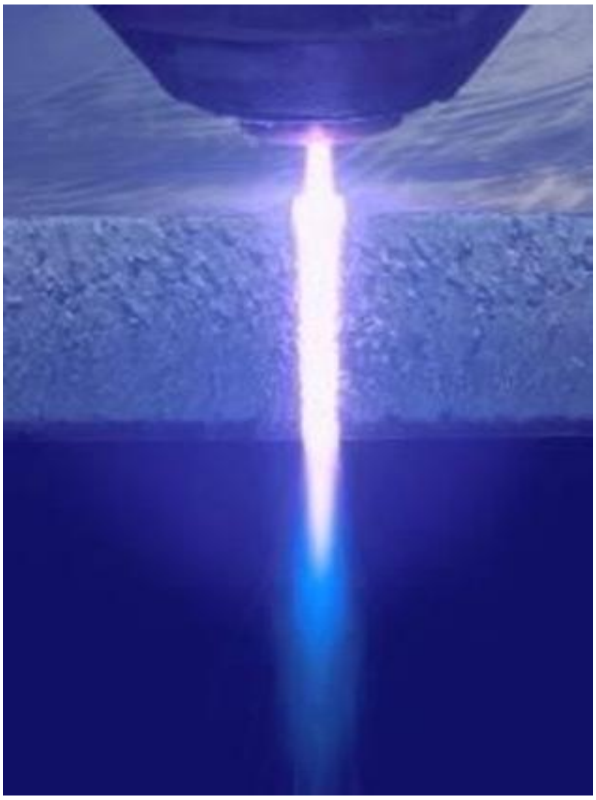


Figure 6. Experience in nuclear power plants **[2]**

Aerosols and fumes are the main safety concern when using thermal cutting methods such as Plasma Arc Cutting (PAC). Maintaining water clarity during underwater PAC is challenging because operators often need to pause cutting to restore visibility through the camera.

Plasma cutting has proven efficient and reliable, enabling decommissioning objectives in contaminated environments. Remote operation significantly reduced radiation exposure for workers. However, the technique requires a dedicated ergonomic control room, as the human-machine interface is critical for safe robotic control. For in-air plasma cutting, ventilation and filtration systems are essential to prevent airborne contamination spread.

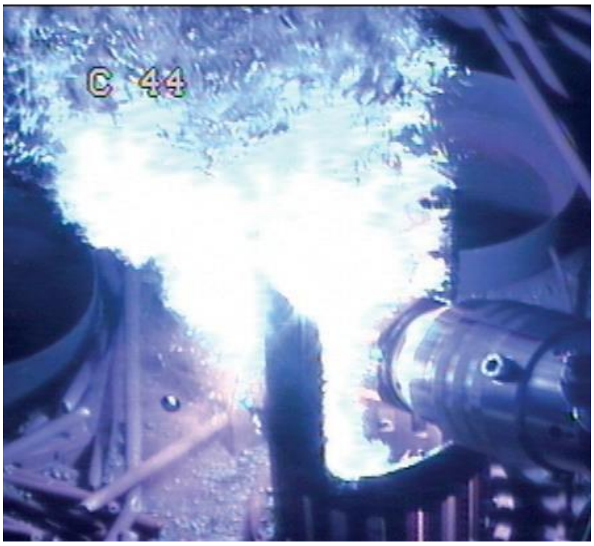


Figure 7. Experience in nuclear power plants **[2]**

EXPERIENCE IN NUCLEAR POWER PLANTS

Plasma cutting has been successfully applied for remote dismantling of reactor pressure vessel internals in several nuclear power plants across Europe and the United States. It has also been used underwater during the dismantling of the multi-purpose research reactor in Karlsruhe, Germany, where cuts were made on components up to 130 mm thick.

Plasma cutting has also been applied in highly contaminated areas, such as during the dismantling of auxiliary systems at Chooz A NPP in France. For these tasks, robotic arms were used, operated remotely with video feedback from a nearby control station. These arms can be equipped with various tools, including plasma torches or hydraulic shears.

Figure 8: Plasma power sources with control board cooling unit and supply lines **[2]**

1.4.2. Contact arc metal cutting (CAMC)

Contact Arc Metal Cutting (CAMC) is an electrical cutting technique that operates at relatively low voltage (below 60 V) and high current levels (typically between 500 and 2000 A). The process relies on the generation of intermittent electric arcs caused by short circuits when the electrode makes contact with the workpiece. These arcs produce intense localized heat, sufficient to melt virtually any metallic material, while electrode wear remains minimal.

A continuous stream of water flows along the electrode, effectively flushing away the molten metal. As the electrode moves along the desired cutting path, it creates a kerf—a narrow slit in the material. Electrodes can be made of either graphite or metal. Graphite offers a key advantage: it does not fuse with the workpiece, preventing the electrode from becoming stuck in the cut.

Electrode geometry is typically tailored to the specific cutting task, with blade-like shapes being the most commonly used. CAMC is not restricted to solid blocks of material; it is also suitable for cutting tube bundles, intricate geometries with varying thicknesses, and even different materials in a single pass.

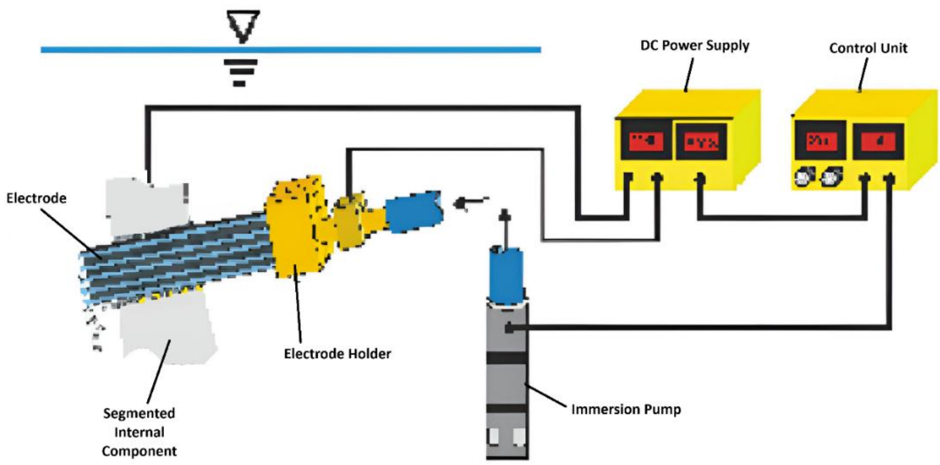


Figure 9: CAMC principle **[2]**

Experience in Nuclear Power Plants

A notable application of CAMC was documented during the decommissioning of the MZFR reactor in Karlsruhe (Bach et al., 2006). In this project, the technique was employed underwater to cut highly activated internal components (such as the support ring of the thermal shield and the moderator tank) within the reactor vessel. The materials ranged in thickness from 35 to 130 mm and were located in close proximity to the reactor wall, which had to remain undamaged throughout the operation.

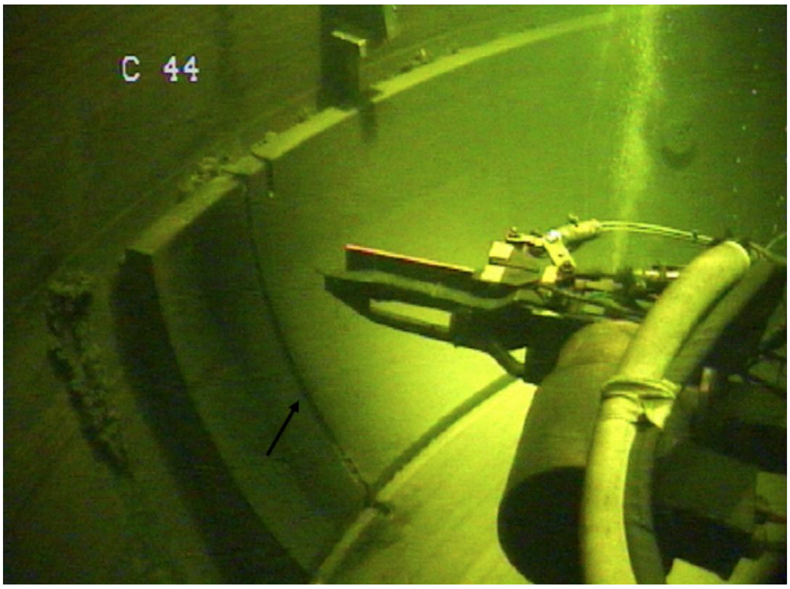


Figure 10: CAMC-assembly with electrode and, at its left, the teaching finger in front of the lower thermal shield wall **[2]**

1.4.3. Flame cutting

Flame cutting is a thermal process used to separate steel components, commonly applied to dismantle reactor pressure vessels. It works by directing oxygen and fuel gases (such as acetylene or propane) through a torch connected to flexible hoses. This method is relatively simple and cost-effective, as the equipment is inexpensive and easy to operate. Mechanical requirements are minimal, making flame cutting suitable for many decommissioning tasks.

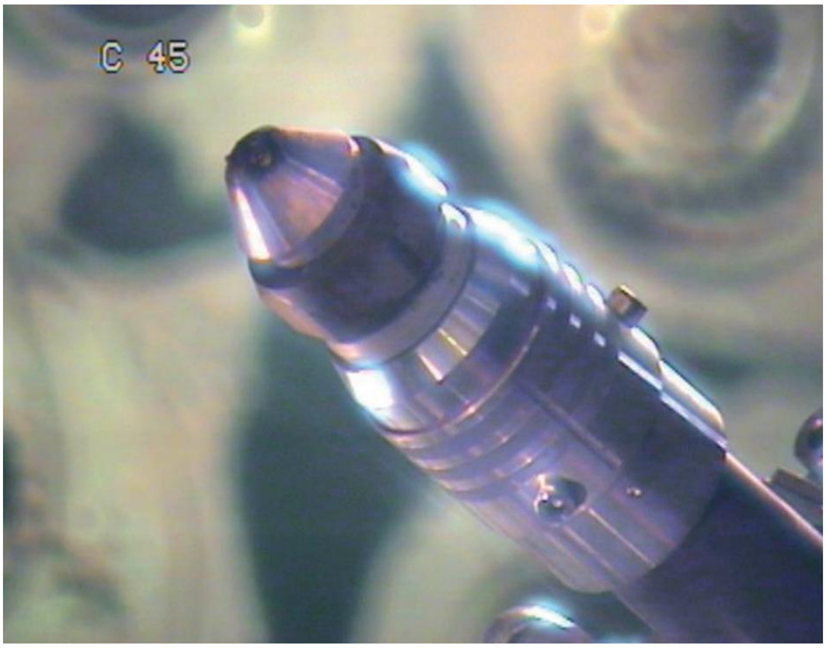


Figure 11: Flame cutting [2]

Flame cutting is highly portable since it does not require complex power supplies. A gas cylinder, torch, and ignition source are sufficient. However, this technique is slower than plasma or water jet cutting and is generally limited to carbon steel. Stainless steel and other alloys typically require alternative methods.

EXPERIENCE IN NUCLEAR POWER PLANTS

Flame cutting is often chosen for dismantling small facilities because of its flexibility and portability. It does not require compressed air or major infrastructure, making it ideal for on-site applications. For example, a 15 kg torch set can cut metal almost anywhere, which is advantageous for remote dismantling tasks.

1.4.4. Laser cutting

Laser cutting is a process that uses a highly focused laser beam to cut various materials by applying energy combined with high-purity technical gases. This technology is unique because laser radiation is extremely concentrated and polarized, with minimal divergence, making it unattainable by other cutting methods. The beam remains stable in time and space, ensuring precision.

Depending on the cutting system, the process can occur through burning, melting, or sublimation. The laser beam is generated by stimulating a lasing material inside a sealed chamber using electrical discharges or lamps. The energy builds up as the beam reflects internally until it escapes as a coherent, monochromatic light. The focused beam typically has a diameter of less than 0.32 mm, allowing kerf widths as small as 0.10 mm, depending on material thickness.

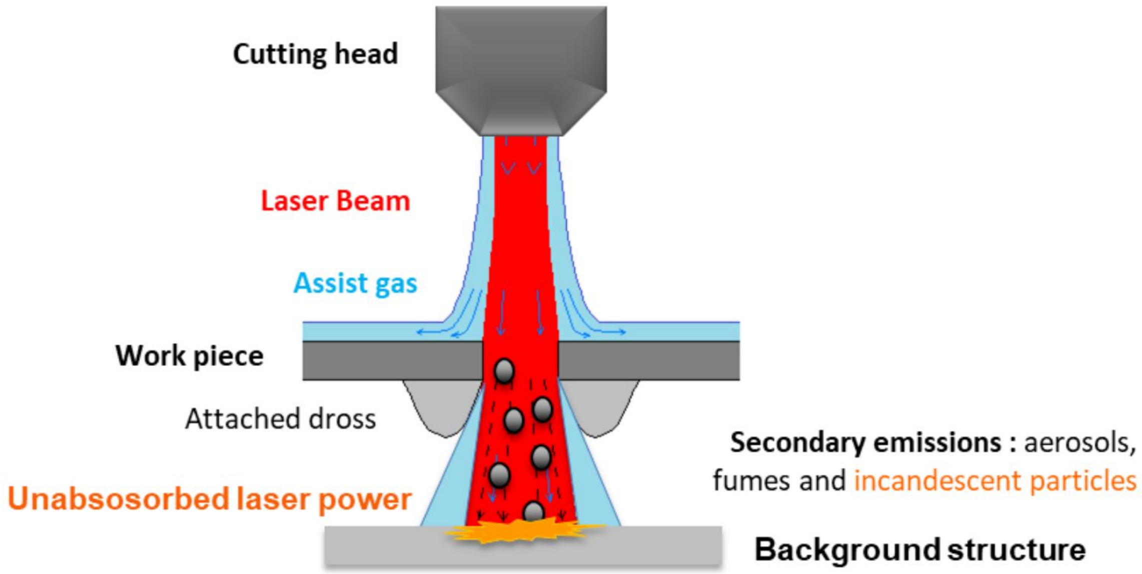


Figure 12: Diagram of the laser cutting system in operation **[3]**

EXPERIENCE IN NUCLEAR POWER PLANTS

The use of laser technology for cutting internal components of nuclear reactors has advanced significantly over the past decade, driven by the need to perform decommissioning operations that are safer, more precise, and generate fewer secondary wastes. Several European and international initiatives (including the LD-SAFE project funded by the European Union, collaborations between CEA and ONET in France, and research by TWI in the United Kingdom) have demonstrated the technical feasibility of laser cutting in complex nuclear environments, particularly for segmenting activated metallic structures within the reactor vessel (Reactor Vessel Internals, RVI).

Experience from these projects shows that high-power fiber lasers (5–10 kW range) can effectively cut stainless steels and special alloys used in reactor internals, offering a competitive alternative to traditional methods such as abrasive water jet (AWJ) cutting, plasma cutting, or mechanical sawing. The main advantage of laser systems lies in their ability to operate remotely via optical fibers, keeping equipment and operators at a safe distance from highly radioactive areas. This reduces occupational radiation doses and enhances overall radiological safety during dismantling operations.

One of the most significant developments has been the demonstration of underwater laser cutting, a common condition during reactor dismantling to minimize radiation exposure and prevent particle dispersion. Dedicated optical heads have been developed to maintain beam quality and control plasma formation in submerged environments. However, trials have also revealed technical challenges — particularly the need to optimize cutting parameters to mitigate beam attenuation in water and properly manage bubble formation and metallic ejection.

In terms of secondary waste generation, studies have shown that laser cutting produces far less solid waste than AWJ, but does generate metallic fumes and aerosols that must be captured by appropriate ventilation and filtration systems. Controlling these emissions is essential to ensure radiological protection and maintain a clean working environment.

1.5. Mechanical Cutting Technologies

1.5.1. Band saw cutting

Band saw cutting is one of the most common methods used to dismantle nuclear facilities. It uses a continuous flat blade that runs around a set of coplanar pulleys, one of which is powered by a motor. The driven pulley moves the blade through friction between the pulley and the blade. The other pulleys are idle pulleys that maintain tension in the blade. A flat section of the blade is usually supported by hardened slotted guides, which keep the blade in contact with the workpiece during cutting. The blade is made from special tool steel and has multiple teeth along its entire length. Different sizes, shapes, and tooth patterns are available for various applications and workpiece materials.

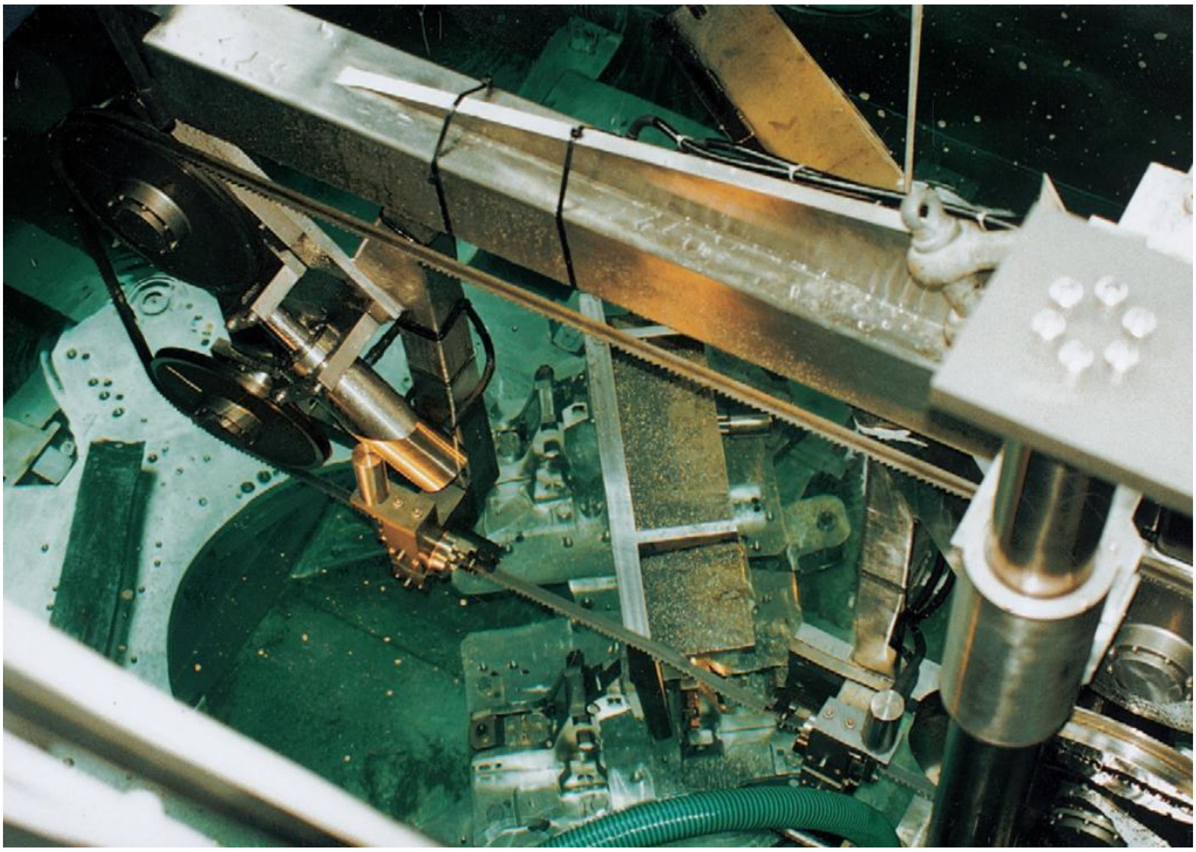


Figure 13: Cold testing of the band saw at the BR3 decommissioning project **[1]**

The simplest and most common form of band saw uses a sawing frame. This type is often used for dismantling components in preparation for further conditioning steps. Thanks to their simple design, these machines are relatively low-cost.

Another type is the band saw with a dual-column guide. A specialized application of this type of saw is dismantling large reactor components. The dual-column saw uses special guide systems for this purpose and separates components directly inside the reactor cavity. These components are much larger than the band saw itself. Stainless steel versions of this saw are suitable for underwater use.

EXPERIENCE IN NUCLEAR POWER PLANTS

Band saw cutting is a slow but reliable method that has been used at decommissioning sites such as TRITON, ATTILA, and EL3. For the TRITON site, the saw was used underwater to cut the reactor grid without contaminating the 800 m³ of water in the reactor pool, allowing it to be released without further treatment. This technique was also used in dismantling reactor internals at Chooz A NPP in France. For these operations, workers used underwater cutting techniques for vessel internals, including band sawing. Operations were controlled remotely from a footbridge above the reactor pool, where workers could operate equipment either directly or via remote video monitoring. Operational feedback indicates that band-sawing enabled the timely dismantling of reactor vessel internals.

From a safety standpoint, this approach has demonstrated efficiency, reliability, and flexibility. The waste was segmented into pieces that met the size specifications required for packaging and conditioning. Water clarity and radioactivity levels were managed through filtration systems, including standard filters and ion-exchange resins. Nevertheless, the process generated liquid effluents and secondary waste (such as spent water filters).

Reports from 2017 noted minor internal contamination among workers, although all cases remained within regulatory dose limits. For instance, at the José Cabrera plant, the upper core barrel was cut using a band saw mounted on a central pillar. The method involved multiple vertical cuts, drilling at the end of one cut, rotating the blade 90°, performing a full 360° horizontal cut, and then removing loosened sections individually. Mechanical cutting offers advantages in reducing secondary waste and improving water clarity, though its cutting speed is slower compared to Plasma Arc or AWJC techniques.

1.5.2. Reciprocating Saw Cutting

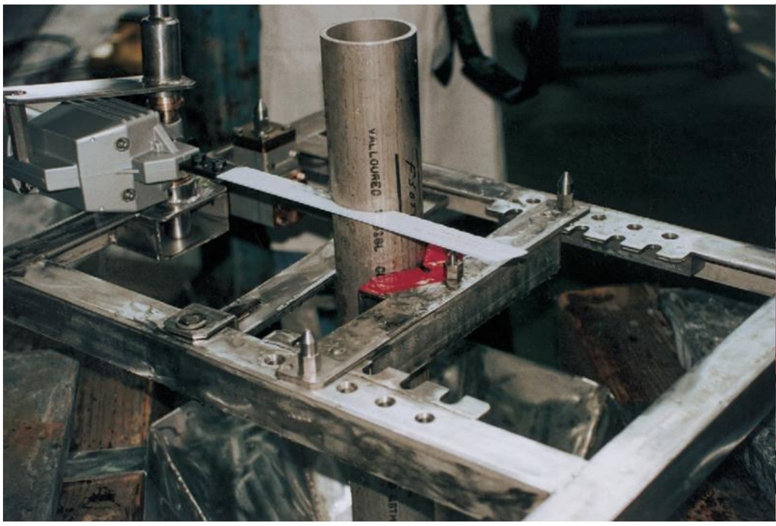
A reciprocating saw cuts by moving a toothed blade back and forth in a linear stroke, removing material on each pass. It produces a narrow kerf, minimal heat, and relatively large particles, which simplifies capture and reduces aerosols; this makes it a “cold-cutting” method well suited to controlled environments and ALARA practices. Systems can be portable (manual, electric, or pneumatic) or stationary, and they support clamps and automatic feed. The guillotine variant precisely guides the blade and controls the cutting force for stable operation.

These saws are used on metals (including stainless steel) and many plastics, in air or underwater, where the medium helps confine particles. Compared to thermal techniques (e.g., plasma arc), cutting hard metals is typically slower, but sparking, heat-affected zones, and residue dispersion are reduced. Performance depends on stroke and frequency, tooth pitch and blade material (bimetal or carbide), feed pressure, and crucially workpiece fixturing to avoid vibration and blade jamming. In active areas, worn blades and swarf are managed as controlled waste.

EXPERIENCE IN NUCLEAR POWER PLANTS

This is a proven technology in nuclear decommissioning worldwide. It has been used at Shippingport for pipe and support sectioning; at BR3 (Belgium) both dry and underwater due to its low heat input and good residue control; and at the Gentilly-1 reactor (Canada), where guillotine saws cut large-diameter ducts and lines with clamping and automatic feed. It was also applied at the experimental BWR units KRB-A and VAK (Germany) for component size reduction [1].

In high-containment tasks—such as remote dismantling of plutonium gloveboxes in the UK—operators combined hacksaws, reciprocating saws, and jigsaws under remote control to minimize aerosols. Recurrent lessons include robust fixturing, correct blade and tooth selection for thickness and hardness, stress-relief precuts in massive sections, and a preference for pneumatic actuation in electrically restricted atmospheres. While not the fastest option, its balance of safety, cleanliness, and compatibility with remote and underwater operation keeps it as a first-line tool for decommissioning and size reduction.



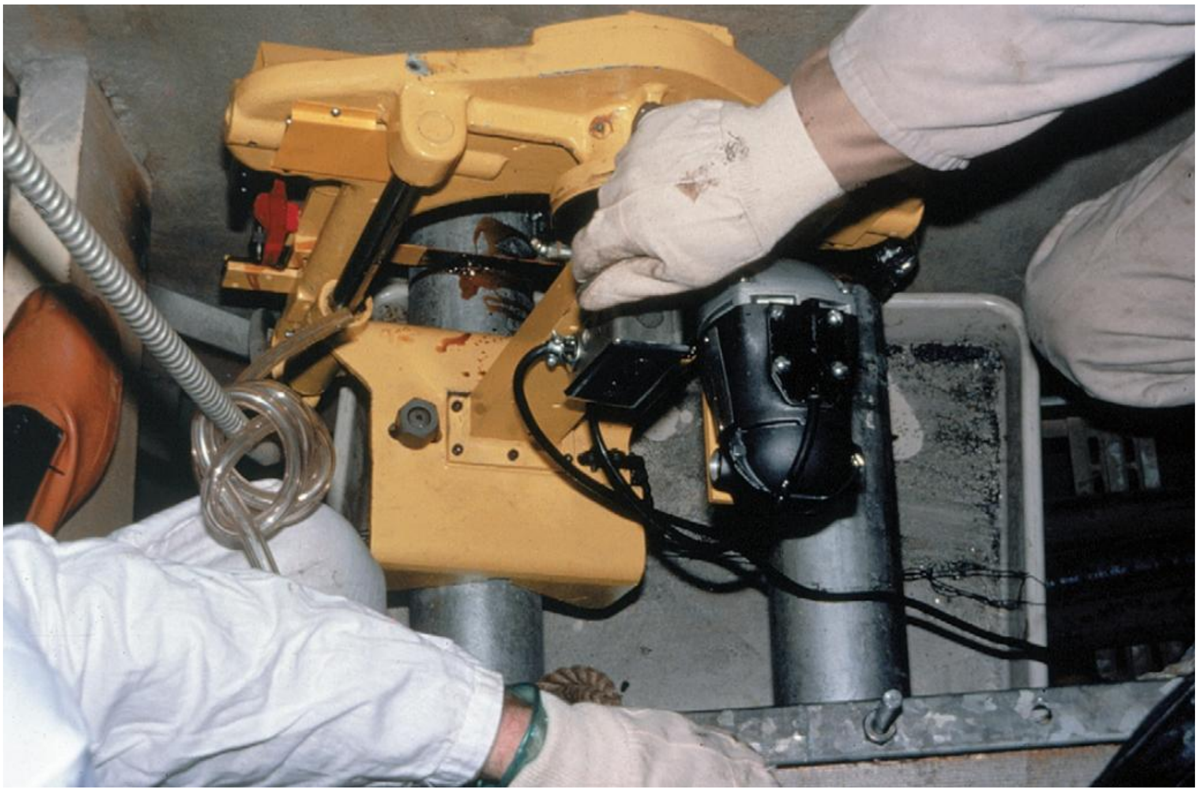


Figure 14: Reciprocating sawing of tubes (remote/underwater application) at the BR3 decommissioning project (Top left); Reciprocating saw in use at the BR3 decommissioning project (Top right); Guillotine saw in use at Gentilly-1, Canada (Bottom) **[1]**

1.5.3. Circular saw

Circular saws are particularly suitable for operations in confined spaces thanks to their compact housing design.

- **Swing-frame circular saw:** This type of saw is mainly used for cutting components into smaller sections after initial dismantling. Its simple construction makes it cost-effective while still offering high technical reliability.
- **Linear-drive circular saw:** Linear-drive circular saws are commonly applied in nuclear decommissioning for dividing large components into sections. Compared to swivel-arm models, they provide a wider operating range and greater flexibility. Stainless steel versions are also appropriate for underwater cutting tasks.

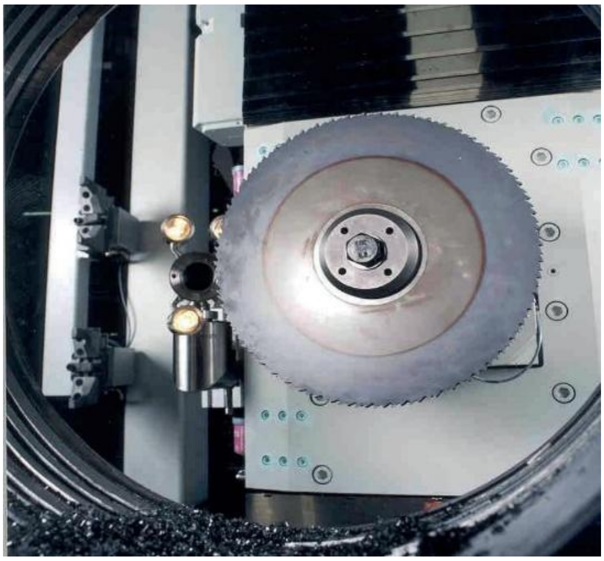


Figure 15. Circular saw **[2]**

EXPERIENCE IN NUCLEAR POWER PLANTS

One major challenge with this technology is the strong force feedback, which can damage robotic arms in remote operations and cause blade blockage during cutting. Additionally, disc wear requires regular replacement, which should be considered when planning cutting activities.

1.5.4. Diamond Cutting

Diamond cutting relies on industrial diamond abrasives embedded in different carriers: beads on diamond wire, segments on circular and wall-saw blades, the cylindrical cutting edge of coring tools, and, in newer systems, the links of diamond chainsaws. The process removes material by controlled abrasion rather than melting, enabling precise, low-heat cuts suitable for controlled environments. Traditionally it has been applied to concrete, reinforced concrete and masonry, and it can operate with liquid coolant to suppress dust or, in more recent developments, in dry mode where water use is restricted. Engineering advances now extend its range to heavily reinforced sections and even pure metal structures. Productivity and cut quality depend on the specification of the diamond medium (grit and bond), the spacing of beads or segments, and the balance between cutting speed and feed force. Wall saws excel in straight, planar cuts; wire saws navigate large or irregular geometries; corers create cylindrical penetrations and samples; and diamond chainsaws are emerging as a portable option where access is constrained.

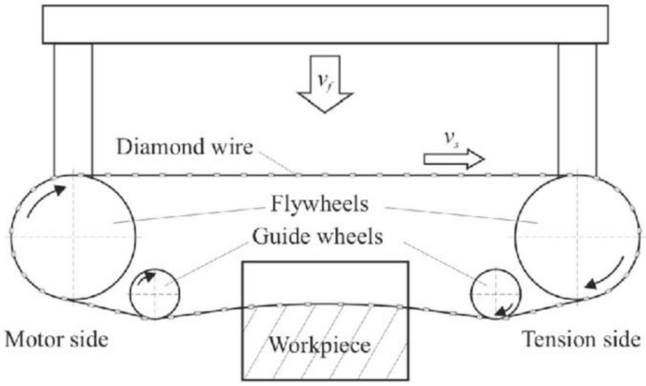


Figure 16: Diagram of a diamond wire cutter

EXPERIENCE IN NUCLEAR POWER PLANTS

Diamond systems are widely proven across nuclear projects. Diamond wire sawing has been used for concrete and masonry at facilities such as the Zimmer NPP and at the FSV reactor, and it enabled the dismantling of the NRX stack in Canada [1]. Programs in Germany reported applications at KKN and at the Grosswelzheim Heissdampfreaktor (HDR), while R&D in Japan has supported the move toward cutting heavily reinforced concrete, pure metal structures, and dry operation without liquid coolant [1]. Wall-saw blades, already standard in civil works, were key to dismantling the biological shield at JPDR and have since been adapted for dry cutting and for metal. Coring tools, constructed similarly to circular diamond blades but in cylindrical form, have been used at HDR for concrete removal and are commonly applied to drill holes, perform stitch-drilling, and extract material samples. More recently, diamond chainsaws have entered the field for cutting concrete and reinforced concrete where portability and manoeuvrability are decisive.

Figure 17: Creating new cell entrances using a diamond cable cutting machine (Top left); Concrete cutting using a diamond tipped blade saw (Top right); Dry cutting of cast iron shielding blocks using diamond tipped blade saw (Bottom) **[1]**

1.5.5. Milling cutters

Milling cutters are primarily used for dismantling tasks and are generally slower than saws. Unlike saws, they do not rely on a linear cutting guide. Various kerf sizes can be achieved depending on the cutter type, making them suitable for removing welds or joints. Several types of milling cutters are commonly applied in decommissioning:

- **End milling cutters:** These cutters are made of high-speed steel or carbide inserts. The kerf is created by rotating the cutter while feeding it into the material until the cut is complete. The cutting depth typically reaches about 30 mm. Their main advantage lies in the flexibility of kerf formation.
- **Side milling cutters:** Side milling cutters produce relatively wide kerfs but only work effectively on straight cuts. Cutting speed depends on the material hardness and the tool's cutting edge. Harder materials require slower speeds to avoid excessive wear.

Figure 18: Milling Cutter **[2]**

<u>EXPERIENCE IN NUCLEAR POWER PLANTS</u>

Milling cutters have been used for underwater cutting at Greifswald during reactor dismantling. Several cutting techniques were combined, including high-power band saws for pre-cutting. Underwater operations required tools such as abrasive water jet systems, band saws, and milling cutters.

The decision to use milling machines was influenced by several factors:

- Thermal cutting was prohibited due to sodium residues.

- Limited space inside the vessel (diameter approx. 2 m).
- Complex geometry of internal components (e.g., reflectors, grid plates).
- High material thickness of certain parts.

The reactor internals had to be dismantled from the inside out, with both the inner and outer vessels removed from the top flange downward.

1.5.6. Hydraulic shear cutting

Hydraulic shear cutting is a mechanical segmentation technique based on the application of opposing compressive forces generated by hydraulic actuators. These forces produce a localized shear stress that exceeds the material's strength limit, resulting in a clean separation without the need for heat or abrasive processes.

The system consists of two blades or jaws driven by a high-pressure hydraulic circuit. The material is placed between the blades, and the hydraulic piston pushes the movable blade until sufficient force is applied to shear the metal. The blade geometry and hydraulic fluid pressure are designed according to the material's properties, thickness, and required precision.

In the nuclear context, this type of tool is often installed in submerged cutting equipment, operating underwater to reduce radiological exposure and minimize the dispersion of contaminated particles. The shear can be remotely operated, mounted on a robotic arm, mobile platform, or crane-type system, thus ensuring personnel safety and cutting accuracy within fuel pools or reactor cavities.

EXPERIENCE IN NUCLEAR POWER PLANTS

Reactor internals—such as the core support, reactor barrel, baffles, or control rod guide structures—feature complex geometries and are made of high-strength stainless steels, typically irradiated for decades. Hydraulic shears allow these components to be sectioned into manageable fragments, suitable for packaging and subsequent handling as radioactive waste.

Key advantages include:

- No thermal generation, avoiding the formation of aerosols, metallic fumes, or redistribution of radioactive contamination.
- High reliability and robustness, capable of cutting thick materials without requiring consumables.
- Low maintenance and compatibility with wet and submerged environments.
- Remote control and repeatability, with minimal risk of mechanical failure.

However, there are also limitations:

- The force required to cut thick components may demand high-power hydraulic systems and robust support structures.
- The cutting process produces plastic deformation at the edges, which can complicate subsequent packaging or stacking of pieces.
- In some cases, limited accessibility within the reactor vessel hinders optimal tool positioning.

Regarding real-world applications, hydraulic shears have been extensively used in decommissioning projects such as Zion (USA), Ringhals (Sweden), and Chooz A (France). In these cases, submerged shear systems were employed to cut the core support and reactor barrel, achieving high cutting rates and significantly reducing collective radiation doses.

Overall, accumulated experience shows that hydraulic shear cutting is an effective, safe, and mature technique for segmenting reactor internals, especially when minimizing radioactive dispersion and ensuring operational robustness are prioritized over geometric cutting precision.

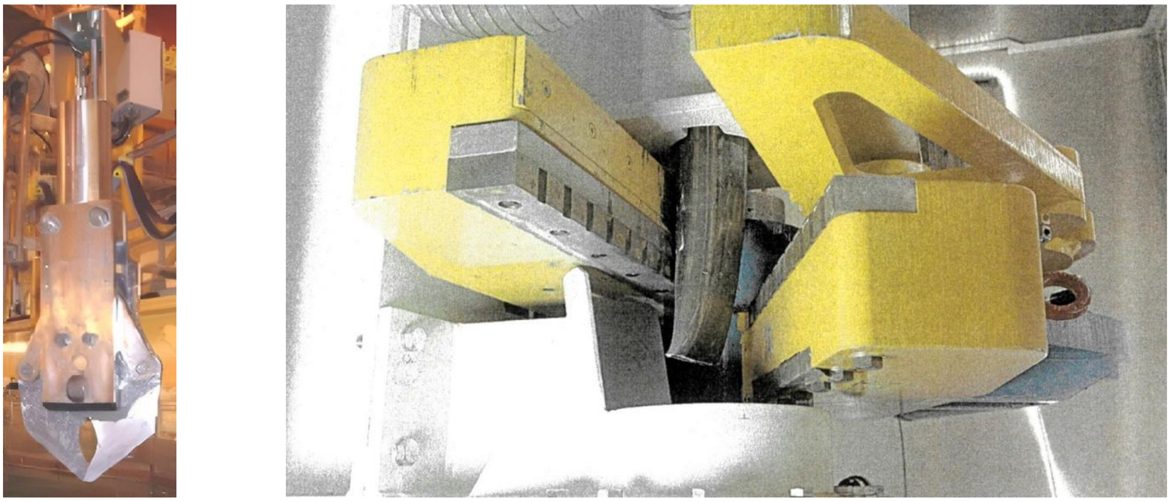


Figure 19: On the left, a hydraulic cutting shear used in the dismantling of the Chooz A nuclear power plant (France); on the right, the hydraulic cutting device used for the segmentation of control rods at the Ågesta nuclear power plant (Sweden) **[4]**

1.6. Qualitative Comparison

	Hydraulic Cutting Technologies	Thermal Cutting Technologies				Mechanical Cutting Technologies			
Technologies	**Abrasive water jet cutting**	**Plasma cutting**	**Flame cutting**	**Contact arc metal cutting**	**Laser Cutting**	**Circular saw**	**Band saw**	**Milling cutters**	**Hydraulic Shear Cutting**
Field of application	Underwater	In air / Underwater	In air / Underwater	In air / Underwater	In air / Underwater	In air / Underwater	In air / Underwater	In air	In air / Underwater
Shape	Complicated shapes	1) Large diameter pipes and tanks, plate and pressure vessels 2) Adaptability to various shapes	1) Large diameter pipes and tanks, plate and pressure vessels, shafts, beams 2) Simple shapes	Small diameter pipes, plates and pressure vessels	Small and large sizes, complicated shapes	Complicated shapes, small diameter pipes	1) Thick structures and wall or floor (<60cm) 2) Pipes, Metal	Simple shapes	Complicated shapes, small diameter pipes
Materials	All materials	Electrically conductive material	Objects with low thermal conductivity	Electrical conductive materials	Homogeneous with no reflective bodies	All materials	All materials	All materials	All materials
Cutting speed	Medium	1) Fast 2) Slower underwater	1) Fast 2) Slower underwater	Slow	Fast	Slow	Slow	Slow	Fast
Cost CAPEX	High	Medium	Low	Medium	Low	Medium	Medium	Low	Low
Required space (remote handling)	Ventilation and separate device for extra high-pressure water formation required	Ventilation and water treatment facilities required	Ventilation facilities required	Ventilation facilities required	Ventilation facilities required	Space required for blade diameter, ventilation and water treatment facilities required	Easy to apply on site with various variations	N/A	Space required for the operation of the hydraulic circuit
Secondary waste	1) Used abrasive post-treatment required 2) Few air pollution 3) Water	1) Working gas (N_2, inert gas) 2) Slag/sludge radiation particles (≈5× mechanical cutting) 3) Large amounts	1) Ferritic oxide (slug) 2) Fumes	Slag/sludge radiation particles (≈5× mechanical cutting	1) Working gas (N_2, inert gas) 2) Slag/sludge radiation particles 3) Large amounts	1) Swarf from the cut material 2) No flame generation, few aerosols	1) Swarf from the cut material 2) No flame generation, no radioactive contamination such as smoke or gas	1) Swarf from the cut material 2) No flame generation, no radioactive contamination such as smoke or gas	No flame generation, no radioactive contamination such as smoke or gas
Liquid secondary wastes	Yes, always (water + abrasive slurry with material fines)	Depends Only with a water table/underwater cutting; otherwise no liquid	Depends Only with a water table; otherwise no liquid	No Unless performed underwater (atypical)	Depends Only with a water table; otherwise no liquid	Depends Yes if using coolant (water-based emulsions or oils); No if using dry cutting	Depends Yes if using coolant (water-based emulsions or oils); No if using dry cutting	Depends Yes if using coolant (water-based emulsions or oils); No if using dry cutting	No Process doesn't produce liquid (oil is maintenance waste, not cutting by-product)
Safety advantages	No airborne contamination	When remotely operated, limitation of radiation exposure	When remotely operated, limitation of radiation exposure	When remotely operated, limitation of radiation exposure	When remotely operated, limitation of radiation exposure	Convenience for adapting cutting pattern to waste package size	Limitation of airborne contamination (in air) or water contamination (underwater)	Limitation of airborne contamination (in air) or water contamination (underwater)	Limitation of airborne contamination (in air) or water contamination (underwater)

Safety drawbacks	Water contamination with small particles	1) Fire hazard and airborne contamination (in air) 2) Radiation protection near filtering systems 3) Water contamination with small particles (underwater)	1) Fire hazard and airborne contamination (in air) 2) Radiation protection near filtering systems 3) Water contamination with small particles (underwater)	1) Fire hazard and airborne contamination (in air) 2) Radiation protection near filtering systems 3) Water contamination with small particles (underwater)	1) Fire hazard and airborne contamination (in air) 2) Radiation protection near filtering systems 3) Water contamination with small particles (underwater)	Thermal risk from friction: pyrophoric hazards associated with Zircaloy and other metals (only during dry cutting)	Thermal risk from friction: pyrophoric hazards associated with Zircaloy and other metals (only during dry cutting)	Thermal risk from friction: pyrophoric hazards associated with Zircaloy and other metals (only during dry cutting)	N/A

2. CASE STUDY

2.1. ESSOR Decommissioning

The ESSOR Reactor is a research reactor located at the JRC site in Ispra (Lake Maggiore, Italy). Conceived in the 1960s, ESSOR entered service in the late 1960s. During its operational lifetime, it was used for tests and experiments on critical reactor and material parameters, and it was shut down in the early 1980s.

For decades, ESSOR has been part of the JRC's comprehensive program for decommissioning and radioactive waste management at the Ispra site. The JRC integrated dismantling activities into its Decommissioning & Waste Management (D&WM) program, which addresses several historic nuclear facilities at the site with a focus on safety, waste minimization, and site recovery. These actions are planned and carried out over many stages and years, given their technical and regulatory complexity.

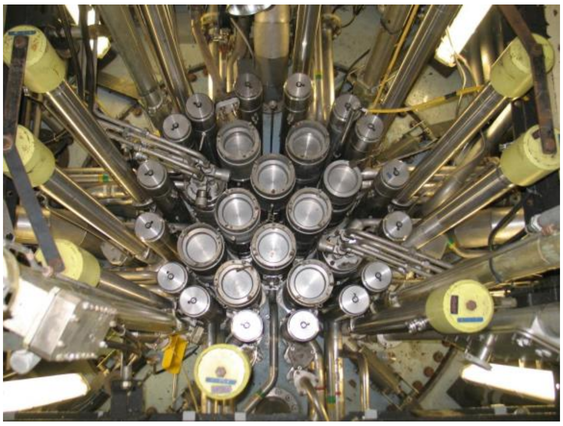


Figure 20: View from the upper reactor chamber [5]

One of the most technically demanding aspects of the ESSOR dismantling process involves the internal components housed within the reactor channels, which were among the most activated elements during operation.

These channels are essentially tubes made of zirconium-based alloys, designed to withstand extreme conditions inside the reactor core. They originally contained fuel elements, control and safety rods, as well as experimental apparatus and irradiation materials used for research purposes.

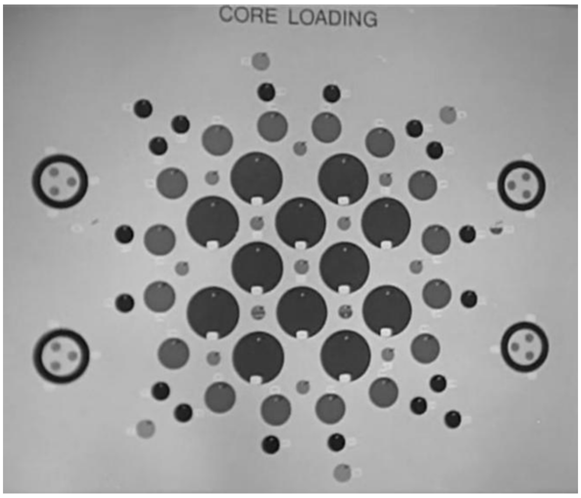


Figure 21: Top view of the reactor core structure and its channels [6]

The reactor core itself was organized into four concentric zones: an experimental zone with irradiation channels and neutron flux plotting channels; a driver zone for fuel elements; a control and safety rods zone with shim rods, fine control rods, and safety rods; and a peripheral zone for reactor instrumentation and experimental equipment. Over the years, several components were removed and replaced with shielding plugs to maintain radiological safety. The extracted components were placed in temporary storage in a pit located within the reactor hall. However, the remaining channels and their associated hardware still represent a significant challenge due to their high activation levels and complex geometry.

To address this challenge, the current plan focuses on developing a specialized machine capable of performing all necessary operations in a fully integrated and remote manner.

This system must be able to cut the zirconium alloy tubes and associated components with precision, ensuring that the segmentation process is clean and minimizes secondary waste. At the same time, it must guarantee the safe handling of highly activated materials, maintaining containment throughout every stage of the operation. Once the components are segmented, the system will transfer them into certified casks designed for radiological safety, ensuring secure storage and compliance with all regulatory requirements. The ultimate goal is to create a solution that operates under strict safety protocols, reduces human exposure to radiation, and combines efficiency with reliability. By integrating cutting, handling, and storage into a single remotely controlled process, this approach will greatly streamline the dismantling workflow and establish a new benchmark for future decommissioning projects.

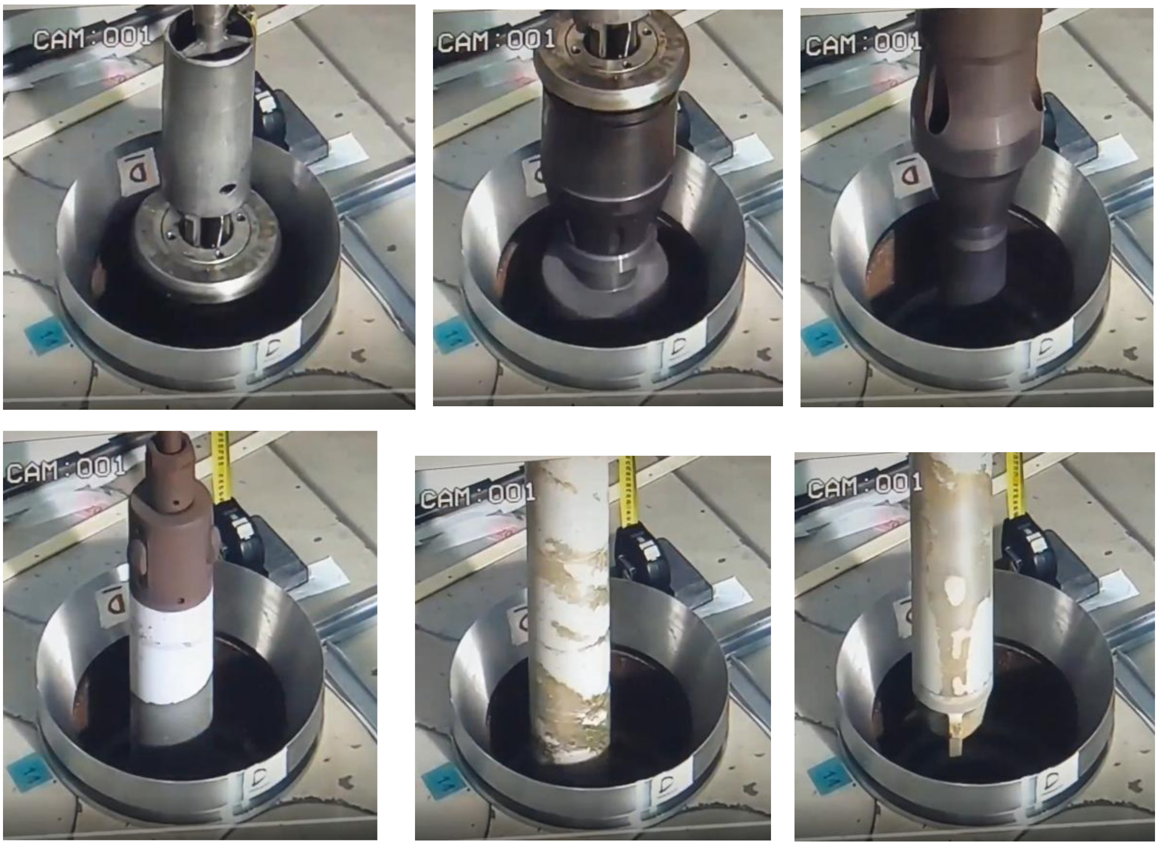


Figure 22: ESSOR snip extraction component from reactor pit **[7]**

The following step consisted in selecting the most suitable cutting technology and, based on that choice, design the cutting system.

2.2. Selection Criteria for Cutting Technology

The wide range of available metal-cutting technologies makes selecting the most suitable option a complex challenge for decision-makers. Each alternative comes with its own advantages and limitations, which must be carefully assessed against the specific requirements of the project.

This is reflected in Table 2, which shows the range of cutting techniques selected in different decommissioning cases, as well as the various reasons that led to their selection. It is important to note that, as shown in the table, cutting solutions are often multiple, and several techniques may be applied within the same case. This is due to the wide variety of components and materials handled during decommissioning, which requires the use of different cutting techniques depending on the specific segmentation requirements.

To support the process of selection, a multi-criteria analysis has been developed to guide the selection of the optimal cutting technology for the dismantling needs and priorities of the ESSOR reactor at the Ispra site.

Table 2: Reactor Internals Segmentation Methods and Selection Drivers Across NPP Projects

NPP (country)	Reactor type	Main cutting technology	Key reasons for selection
José Cabrera / Zorita (Spain) [8] [9]	PWR	Underwater mechanical cutting (band saws, disk saws, shears)	Water shielding (ALARA) and dose control; minimal secondary waste with good chip collection/visibility; proven via mock-up testing before site work; aligned with packaging strategy (GWC and CE-2a/2b)
Zion (USA) [10] [11]	PWR	Remote underwater mechanical segmentation (milling, drilling, saws; custom tools like C-HORCE)	Fully remote, flooded-cavity operations for radiological protection; schedule/cost optimization; purpose-built tools for circumferential cuts and volume reduction
BR3 (Belgium) [12] [13]	PWR (prototype)	Underwater mechanical sawing/milling (band and circular saws; AWJ used selectively)	EU pilot: strong ALARA and waste minimization focus; underwater methods demonstrated technical feasibility vs thermal techniques; chosen for lower secondary waste and controlled swarf handling
Barsebäck 2 (Sweden) [14] [15]	BWR	Underwater mechanical cutting (hydraulic shears, band & disk saws)	High dose fields ⇒ fully remote tools and submerged work; enhanced filtration to maintain water clarity; first Swedish commercial NPP dismantling
Maine Yankee (USA) [16]	PWR	Abrasive Water Jet (AWJ) underwater + mechanical	Low exposure to workers; no added pool-water cleanup and minimal secondary waste vs thermal methods; approach informed subsequent PWR projects (Yankee Rowe, Connecticut Yankee)
Vermont Yankee (USA) [17]	BWR	AWJ for most internals; diamond-wire for large/complex pieces	AWJ gives precision and low reaction forces in highly activated, hard-to-reach areas; enabled dense, efficient packing; local logistics favored full segmentation over near-intact vessel removal

Rancho Seco (USA) [18]	PWR	Underwater mechanical cutting (sawing, machining, milling, shearing)	Low dose, no extra pool-water cleanup costs, and negligible secondary waste; extensive pre-planning/testing ensured steady cutting rates and controlled chip management
San Onofre Unit 1 (USA)	PWR	Remote mechanical cutting (five-axis gantry manipulator; mechanical saws/tools)	Maximized cavity space and logistics (manipulator on refueling bridge rails); reduced equipment contamination and secondary waste vs abrasive/thermal; supported continuous operations and ALARA

2.2.1. Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis (MDA) is a structured approach designed to assist decision-making by systematically comparing the strengths and weaknesses of different alternatives. Its purpose is to identify the most appropriate solution within a limited timeframe, especially when the decision involves conflicting objectives or preferences. MDA achieves this by aggregating qualitative and quantitative factors, enabling a clear evaluation of trade-offs between competing goals. The comparison of alternatives is based on a set of explicitly defined criteria that reflect the aspects most relevant to the decision. In essence, MDA frames the decision problem and illustrates how each option performs across all selected criteria, providing a transparent and rational basis for choice.

For this analysis, the Weighted Sum Model has been adopted as the decision-making method. This model combines qualitative and quantitative factors, assigning weights to each criterion according to its relative importance. By doing so, it creates a clear and comprehensible framework for evaluating alternatives and selecting the option that best meets project objectives.

The methodology consists of five sequential steps:

I. **Define the criteria**: Identify all relevant criteria that will influence the decision. These should include both quantitative aspects that can be measured and qualitative factors that reflect non-measurable considerations.
II. **Assign weights**: Determine the relative importance of each criterion by assigning appropriate weights. This step ensures that the most critical factors have a greater influence on the final decision.
III. **Evaluate the alternatives**: Assess each option against the defined criteria by assigning performance scores. These scores should accurately reflect how well each alternative meets the requirements of each criterion.
IV. **Calculate the overall score**: Combine the performance scores with their corresponding weights to compute the total score for each alternative. This provides a clear, comparable measure of overall benefit.
V. **Select the optimal alternative**: Identify the option with the highest total score as the most suitable choice, ensuring that the decision is based on a balanced and transparent evaluation process.

2.2.2. Criteria specification

The criteria defined for decision-making must be valid, reliable, and relevant to both decision-makers and stakeholders. Ideally, they should also be preferentially independent, as explained below. To ensure consistency, the criteria must be structured to avoid double-counting and minimize any overlap. Based on the assessment objectives, the following set of criteria has been established: reliability, safety, cost, performance, complexity and applicability, operational skills, data availability, individual and collective dose, waste volume and number of casks, and the use of liquids.

2.2.3. Weighting according to importance

In the second step, each criterion is assigned a weight that reflects its relative importance in achieving the project objectives. A numerical scale from 1 to 10 is used for this purpose, where higher values indicate greater significance. The weighting scale is defined as follows:

1–2: Equally important

3–4: Moderately important

5–6: Strongly important

7–8: Very strongly important

9–10: Extremely important

Table 3: Parameters importance and weighting

Parameter	Importance	Weight	%
Reliability	Very strongly important	9	15,79
Safety	Extremely important	10	17,54
Costs	Moderately important	4	7,02
Performance	Strongly important	5	8,77
Complexity	Moderately important	4	7,02
Operational skills	Equally important	2	3,51
Data availability	Equally important	2	3,51
Use of liquids	Very strongly important	8	14,04
Secondary waste volume	Strongly important	5	8,77
Individual/collective dose	Very strongly important	8	14,04

2.2.4. Analysed alternatives

Most of the metal components scheduled for fragmentation in the ESSOR reactor are activated and/or contaminated. Given the critical nature of cutting INE components and the JRC-Ispra site's limited capacity to handle large volumes of liquid radioactive waste, the analysis was confined to mechanical cutting technologies. The following options were evaluated in the multi-criteria analysis: Reciprocating saw cutting, diamond wire cutting, shear cutting, and circular saw cutting.

Table 4: Parameters and quality assessment of technologies

Parameter/ Technology	Reciprocating saw	Cutting shear	Circular saw	Diamond wire
Reliability	6,8	8,4	6,2	5,8
Safety	7	8,4	6	5,4
Costs	7,6	5,4	8	5,4
Performance	5	8,6	5,6	6,6
Complexity, applicability	7,2	7,2	8	6,2
Operational skills	6,6	7,6	7,2	5,6
Data availability	4,8	7,6	7,2	6,6

Use of liquids	6	9,4	5	4,2
Waste volume	5,4	9,4	5,6	5
Individual/collective dose	6,4	8,2	6,8	5,8

2.2.5. Benefit calculations

A weighted sum is used to reflect the relative importance of individual data points in the decision-making process. Unlike a simple summation, where each value contributes equally, a weighted sum assigns a specific weight to each data point, giving greater influence to those considered more significant. This method ensures that the final score represents both the performance of each alternative and the priority of the criteria.

The calculation is performed by multiplying each data point by its corresponding weight and then summing the resulting products, as shown in the following equation:

$$S = \sum_{i=0}^{n} Wi * Xi$$

Where:

- **S** is the weighted sum (overall score),
- $\mathbf{X_i}$ is the value or score of the alternative for criterion *i*,
- $\mathbf{W_i}$ is the weight assigned to criterion *i*,
- **n** is the total number of criteria considered.

2.2.6. Best alternative selection

Using a Multi-Criteria Decision Analysis framework, three cutting technologies were evaluated against seven criteria for application at the ISPRA reactor. Weighted scores were computed for each technology; those achieving a score > 7 were classified as Highly Recommended. The suitability ratings are based on input from five respondents—decommissioning personnel in charge of the dismantling activities—whose judgments reflect their professional opinions and prior hands-on experience with the assessed technologies. This approach strengthens decision-making and provides a comprehensive view of the parameters that should guide technology selection in line with project needs and priorities.

Table 5: Results of multicriterial assessment

Technology	Reciprocating saw					Cutting shear					Circular saw					Diamond wire				
Respondent	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Reliability	1,1	1,3	1,1	0,5	1,4	1,4	1,4	1,1	1,3	1,4	0,8	1,4	1,1	0,5	1,1	1,1	1,4	0,5	0,5	1,1
Safety	1,4	1,2	1,4	0,7	1,4	1,4	1,6	1,6	1,4	1,4	1,4	1,4	0,9	0,7	0,9	1,1	1,2	0,9	0,7	0,9
Costs	0,6	0,4	0,5	0,6	0,6	0,4	0,6	0,6	0,1	0,3	0,5	0,6	0,6	0,6	0,6	0,2	0,5	0,2	0,4	0,6
Performance	0,4	0,6	0,4	0,2	0,5	0,7	0,8	0,8	0,8	0,7	0,4	0,7	0,4	0,2	0,7	0,9	0,7	0,3	0,3	0,8
Complexity, applicability	0,6	0,4	0,4	0,6	0,6	0,6	0,6	0,4	0,4	0,6	0,6	0,6	0,6	0,5	0,6	0,3	0,5	0,5	0,4	0,5
Operational skills	0,3	0,0	0,3	0,3	0,3	0,3	0,3	0,3	0,2	0,3	0,3	0,3	0,2	0,3	0,3	0,1	0,3	0,3	0,1	0,2
Data availability	0,1	0,0	0,2	0,2	0,3	0,3	0,3	0,3	0,3	0,3	0,4	0,3	0,2	0,2	0,3	0,2	0,3	0,2	0,2	0,3
Use of liquids	1,0	1,1	0,7	0,3	1,1	1,4	1,4	1,1	1,4	1,3	0,3	1,1	1,3	0,1	0,7	0,3	1,1	0,7	0,1	0,7
Waste volume	0,4	0,5	0,4	0,5	0,5	0,9	0,9	0,8	0,8	0,8	0,4	0,6	0,4	0,5	0,5	0,3	0,6	0,3	0,5	0,5
Individual/collective dose	1,0	1,1	0,7	0,6	1,1	1,0	1,3	1,1	1,3	1,1	1,0	1,1	1,3	0,6	0,8	0,7	1,1	0,4	1,0	0,8
SCORE	**6,9**	**6,8**	**6,0**	**4,5**	**7,8**	**8,3**	**9,0**	**8,1**	**7,9**	**8,1**	**6,0**	**8,1**	**6,8**	**4,2**	**6,4**	**5,1**	**7,7**	**4,1**	**4,2**	**6,4**

To facilitate interpretation and ensure a clear understanding of the outcomes, each technology is classified according to its final index and grouped into categories with corresponding colour codes. The classification is as follows:

- **7.0–10.0:** Highly recommended
- **5.0–7.0:** Adequate
- **2.5–5.0:** Poorly adequate
- **0.0–2.5:** Inadequate

Table 6: Multicriteria analysis results - overview

Technology	Reciprocating saw	Cutting shear	Circular saw	Diamond wire
Respondent 1	6,9	8,3	6,0	5,1
Respondent 2	6,8	9,0	8,1	7,8
Respondent 3	6,0	8,1	6,8	4,1
Respondent 4	4,5	7,9	4,2	4,3
Respondent 5	7,8	8,1	6,4	6,4
Average sum	**6,4**	**8,3**	**6,3**	**5,5**
Result of assessment	**Adequate**	**Highly recommended**	**Adequate**	**Poorly adequate**

Shear cutting was identified as the most suitable method for the specified purpose. This technology consistently achieved the highest scores in key areas such as nuclear safety, absence of liquid use, low waste volume, and effective radiation protection. It generates no radioactive by-products or aerosols and offers a high level of reliability, which translates into reduced time spent in controlled areas during service operations.

2.3. Description of the Developed Solution

The machine designed for the ESSOR project constitutes an integrated system for the segmentation, transfer, characterization, and storage of the reactor's internal components after being cut by a hydraulic shear. The design aims to ensure controlled and isolated operation, guaranteeing radiological containment throughout all process phases and optimizing material flow from the cutting point to its final confinement in drums or shielded casks.

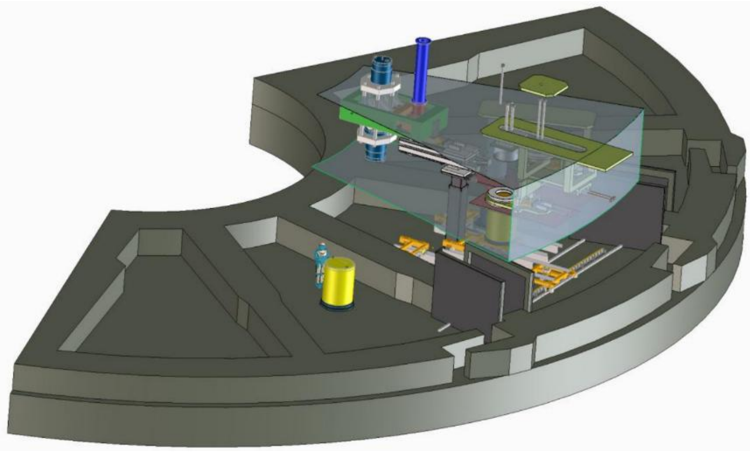


Figure 23: Overview of the internal components segmentation and management system

The facility is distributed across three interconnected spaces with sealable openings: Room 1103, dedicated to cask preparation and housing hydraulic and electrical systems; Room 1104, the operational core of the system, divided into clean and contaminated zones by a transparent enclosure; and finally Room 1105, used as the final storage area for loaded casks. A logistics system operates between these rooms based on two mobile platforms: a main cart that connects the three rooms longitudinally and a secondary cart that moves transversely to precisely position each cask under its corresponding station. This system enables the movement of both drums and shielded casks, compensating for geometric differences through specific bases.

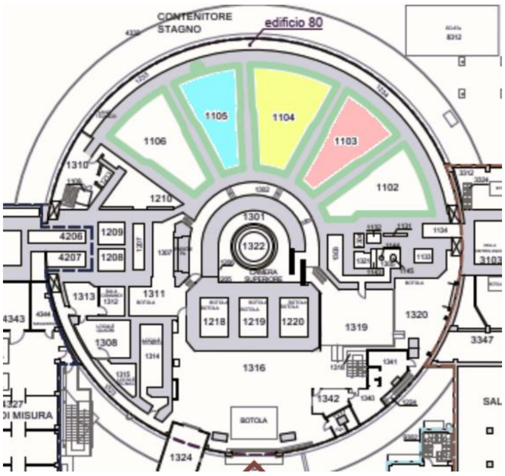


Figure 24: Casemates of the containment building. Room 1103 (red) houses the cask preparation area along with hydraulic and electrical systems, room 1104 (yellow) contains the system's operational core, and Room 1105 (blue) serves as the final storage area for loaded cask. The central circle represents the reactor.

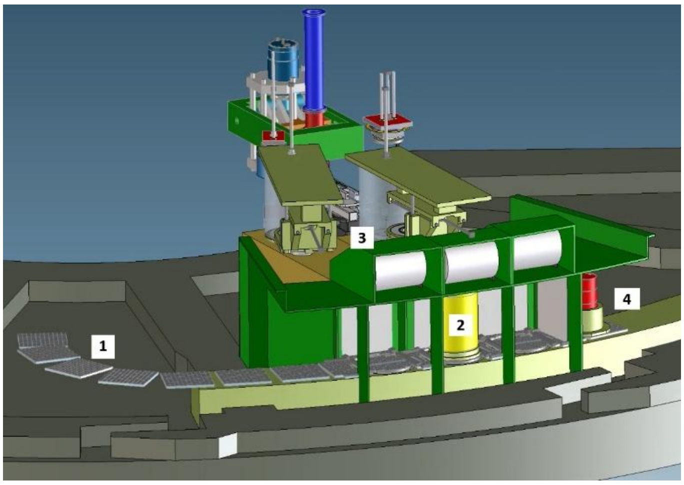


Figure 25: The empty cask is placed on the conveyor belt in Room 1103 (Section 1) and then moved to Room 1104, where the cutting machine is located. There, the belt transports the cask to its designated gate (Section 2). Once at the gate, it opens, and another conveyor belt carries the cask inside to the reception area for the segmented components. At this point, the machine opens the cask, fills it with the cut component pieces, and closes the lid (Section 3). Finally, the cask returns to the main conveyor belt and is transported to the storage room, 1105 (Section 4).

Once the cask is introduced into Room 1103 through the upper hatch and prepared—meaning the lid is removed in the case of casks or a temporary lid is installed for drums—it is transferred to Room 1104. There, three reception stations exist: one for shielded casks, another for unshielded casks, and a third for drums. Each station features a lifting system that partially inserts the cask into an opening located in the contaminated zone's ceiling. Tightness between the cask and the opening is ensured by inflatable seals. A magnetic lifting system allows lids to be removed or installed with minimal interaction with the contaminated area, and a protective funnel is placed over the cask to direct the cut material without leaks.

Material handling is performed by a rotary basket system located beneath the hydraulic shear. This basket can align with three possible outlets depending on fragment size. A sliding gate controls the material's fall into the basket, and once the programmed volume is filled, a sensor inserted through the upper valve measures radiation levels to determine classification. The basket then moves to the assigned station, couples with the funnel installed on the cask, and coordinated gates open to allow material transfer without spillage. Once emptied, the basket undergoes an automated cleaning cycle at an ascending station equipped with a controlled washing system, ensuring no external residue compromises subsequent processes or causes cross-contamination.

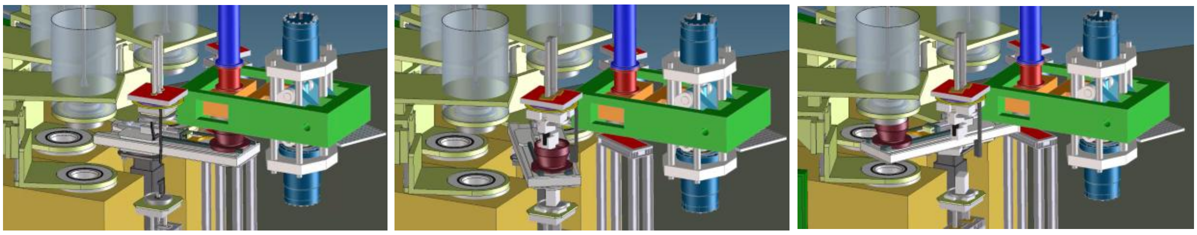


Figure 26: Rotary basket system. From left to right, the rotary basket system is aligned with the hydraulic shear to receive the fragments of the sectioned component. Once filled, it moves to the radiological characterization area. After the waste is catalogued, the rotary basket continues rotating until it reaches the reception gate of the corresponding cask, where it locks into position and releases its contents into the cask through a bottom hatch.

The process continues iteratively until each cask is fully loaded. Once completed, the openings are sealed, the lid is reinstalled using the magnetic system, and the cask is transferred to Room 1105, where it remains stored for later dismantling stages.

Overall, the machine defines a closed, modular, and automated system that combines remote handling, progressive containment, classification-based segregation, and integrated cleaning. This design reduces operational exposure, guarantees radiological traceability, and provides a complete industrial solution for the safe management of segmented waste from the ESSOR reactor's internal components.

The design herein is a reference, non-definitive version. It may be updated during subsequent engineering and/or licensing phases; however, the functional concept and overall layout are expected to remain essentially unchanged, with local adjustments as needed.

2.4. Comparison With Other Cases

2.4.1. Ågesta

The Ågesta case describes the dismantling of Sweden's first commercial nuclear reactor, located in an underground cavern near Stockholm. It operated between 1964 and 1974, producing electricity and district heating, and has since remained in a maintenance state. The dismantling plan, launched in 2020, involves removing the radioactive components through a process that prioritizes safety and waste reduction.

One of the greatest challenges was handling 27 thick control rods, each five meters long with an absorber core (three meters long) made of silver, indium, and cadmium—highly activated and with surface dose rates exceeding 1000 mSv/h. There were no standard solutions for their handling, transport, or segmentation, so Vattenfall designed its own method based on in-situ segmentation using remotely operated equipment. Modular tools, radiological protection systems, and procedures were developed to minimize exposure (ALARA), including shields, cameras, and remote controls. [4]

The process involved cutting the absorbers into segments of approximately 125 mm using powerful hydraulic shears, packing them into shielded barrels, and transferring them to interim storage.

Preliminary tests and adjustments were essential to address issues such as segment deformation and locking mechanisms. It was also observed that when the rods were cut into these short segments, the deformation produced by the hydraulic shear naturally flattened the pieces, reducing their volume and improving storage efficiency.

In addition to the absorber sections, the activated—but non-absorbing—parts of the control rods were also segmented. However, these pieces were placed in separate containers from the absorber-containing segments, because their radiological levels were significantly lower. Storing them together could have unnecessarily contaminated the lower-activity pieces.

The control rod dummy unit will be donated to the Technical Museum in Stockholm, along with some other artefacts from Ågesta.

This project stands out for its innovative approach: combining standard technology with custom solutions to operate in a confined space with high radiation levels. The concept of cutting the components using hydraulic shears was largely inspired by the extensive experience with this technology in the non-nuclear industry. This gave the project significant added value, as it facilitated the adoption of a new cutting methodology within the nuclear sector. The complete dismantling of the reactor and its systems continued until 2025, with the goal of leaving the cavern clean and sealed for its return to the city of Stockholm.

The system developed to manage the control rods at Ågesta functioned as an integrated solution that combined radiological protection, remote handling, and controlled segmentation to minimize risks and reduce waste volume.

First, each rod was inserted into a six-meter radiological protection tube, suspended by a special yoke and the plant's main crane. This tube acted as shielding during transfer to the cutting area. The entire process was remotely controlled from the reactor hall using cameras and sensors, avoiding direct personnel exposure.

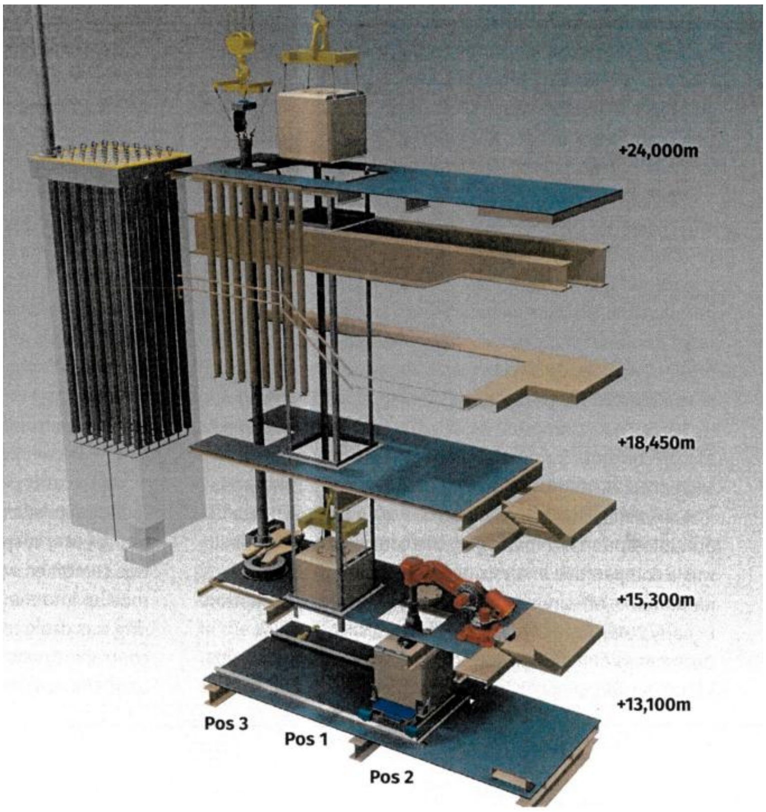


Figure 27: Control rod segmentation rig **[4]**

Once the rod was positioned, a high-power hydraulic shear system was used to cut the absorber into segments of about 125 mm. This method was chosen because it did not generate heat or significant secondary waste. The cutting area was enclosed within a structure with steel and polycarbonate panels, equipped with filtered ventilation to contain any released contamination.

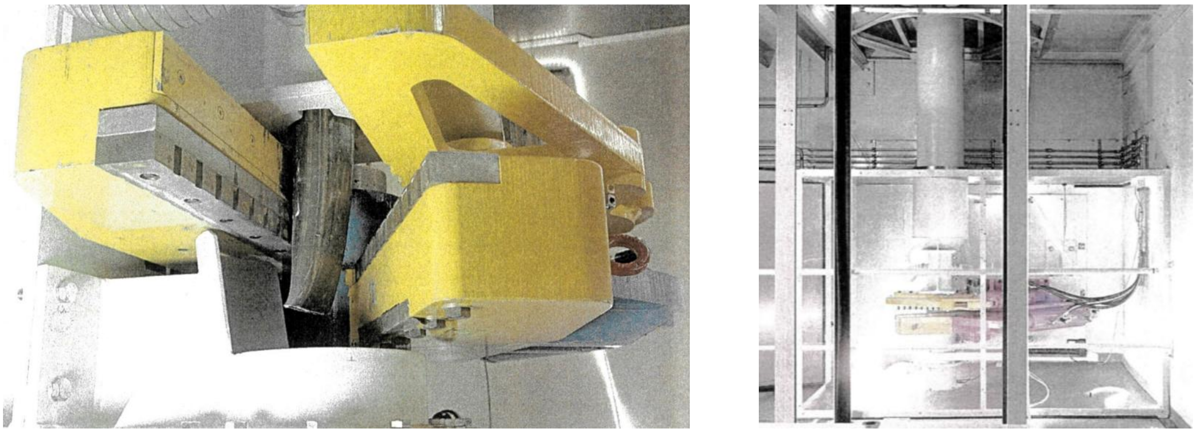


Figure 28: Above left: Control rod in cutting position. Above right: Cutting station showing enclosure to stop spreading of contamination **[4]**

The segments were placed directly into shielded barrels inside a concrete mold, using a lifting table and rail system that allowed containers to move between positions without manual intervention. Barrel closure was performed by an industrial robot programmed to place the lids and secure the locking mechanisms precisely, using cameras and laser pointers for alignment.

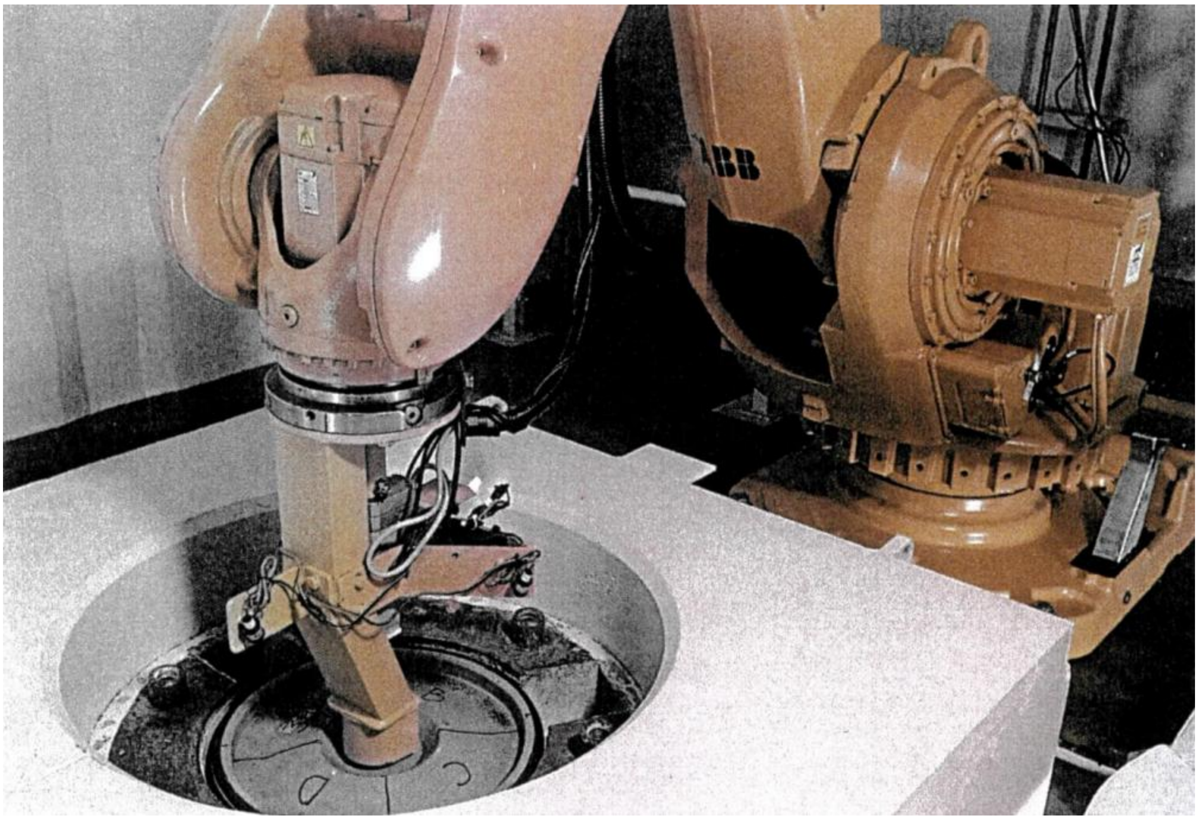


Figure 29: Robot mounting a lid **[4]**

2.4.2. ESSOR versus Ågesta

Ågesta also proposes an integrated solution in which the implemented solution handles both the segmentation of activated components and their storage. However, it is important to highlight a key difference: the technical complexity between the two projects. In the case of Ågesta, the machine design is significantly simpler than in the ESSOR project. This simplicity brings clear advantages, such as greater ease in system design and manufacturing, which translates into a notable reduction in time and costs.

This difference is not solely due to engineering decisions but to distinct technical requirements. In ESSOR, the elements that need to be segmented and managed exhibit greater geometric variety and more complex distributions within the reactor, which in turn implies a considerably higher radiological diversity than in Ågesta. This complexity makes a binary solution like the one used in Ågesta unfeasible, where the machine only separates two fractions: the lower part of the control rods, which is highly activated, and the upper part or heads, with lower activity levels.

In contrast, the heterogeneous nature of ESSOR's components requires a more complex system, capable not only of segmenting the material but also of measuring its radiological activity in situ and classifying it into three differentiated outputs based on its radiological inventory. This greater capacity for analysis and segregation is essential to properly manage the complexity of the material processed in ESSOR.

2.4.3. Mobile hydraulic shears

In most cases where hydraulic shears are used for segmenting internal components, their application is much simpler than in the ESSOR project. A common method involves performing the segmentation underwater, as shown in Figure 30 and Figure 31, which illustrate the use of a hydraulic shear to cut the Core Spray and Core Grid at the Forsmark nuclear power plant during a mid-life outage [19]. In these scenarios, the machines used are limited exclusively to cutting functions, so the subsequent handling of segmented material must be carried out using complementary systems, meaning these are not integrated solutions.

Figure 30: Shearing tools used to cut the core spray system and flat bars on the core grid **[19]**

This approach is common in the dismantling of light-water reactors, where the vessel can be flooded and has sufficient internal volume to allow the safe and operational use of mobile shears. In contrast, in ESSOR, being a channel-type reactor, the geometric and operational conditions make it impossible to apply this methodology. The internal configuration does not allow access, movement, or efficient operation of mobile shears, which forces the use of segmentation systems specifically designed for its structural and radiological particularities.

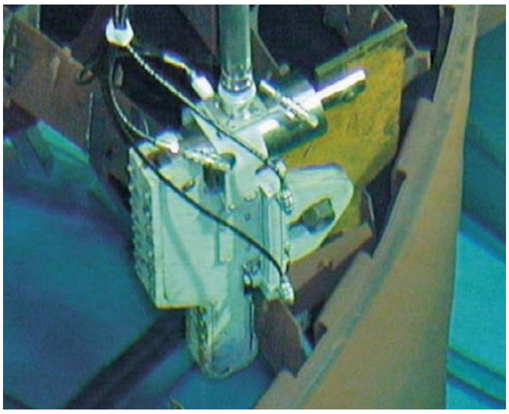


Figure 31: Hydraulic Shears being used for cutting of the Core Grid removed from the Forsmark NPP [19]

Mobile hydraulic shears offer significant advantages for certain tasks: for cutting long and slender elements such as rods or pipes, and for relatively thin sections of core support grids, sawing is not necessary since these sections can be cut directly with shears. The main benefit is that they do not generate secondary waste during cutting, reducing process complexity. Additionally, shears are specifically designed for each task, ensuring clean cuts and easy positioning on the pieces to be segmented.

At Forsmark, for example, a lightweight 40 kg tool, standard from the subcontractor Nike Hydraulics, with a top connection designed by Westinghouse, was used. This shear, operated by two people, made approximately 340 cuts on 8 mm thick plates to dismantle the grid structure, leaving only the outer ring, which was later cut with a band saw. The lightweight tool can cut pipes up to 90×2.5 mm and flat bars of 100×8 mm, with a cutting force of 314 kN at 700 bar. For larger sections, a heavy 210 kg tool was used, capable of cutting irradiated pipes of 120×4 mm and flat bars of 130×10 mm, with a force of 1,000 kN at 800 bar. It is estimated that it could cut up to 130×5 mm in pipes and 140×12 mm in flat bars of irradiated AISI 304 steel without needing blade replacement after multiple cuts.

These tools have also been used in other projects, such as the dismantling of the BR-3 reactor in Belgium, where it was demonstrated that they could be operated with long handles at distances of up to 7 meters, increasing their versatility in complex radiological environments.

2.4.4. Măgurele research reactor

In Măgurele, Romania, the dismantling of a VVR-S-60 research reactor was carried out under the Research Reactor Decommissioning Demonstration Project (R²D²P) promoted by the IAEA [20]. In this case, the segmentation and handling of the reactor's internal components were performed mostly through manual procedures. The control rods and guide tubes were removed with crane assistance and subsequently segmented using a manually operated hydraulic shear.

Figure 32: Lifting the control rod from the core (left) and cutting the control rods with the Holmatro scissors into 220 litre drums (right) **[21]**

However, some components with significantly higher activation levels, such as the automatic regulator rod, required remote handling techniques. For this purpose, a combination of a conventional crane and a remotely controlled crane—Brokk 160 model—equipped with a specialized tool for component segmentation was used. Once processed, the material was transferred to a special lead-shielded container for safe storage.

Figure 33: Placement and operation of the Brokk 160 **[21]**

Although this approach proved functional for the scale of the project, it presents significant limitations that prevent its application in the case of ESSOR. While the solution used in Măgurele was considerably simpler and required a very low economic investment, it entails major drawbacks. First, operators were exposed—although within established radioprotection limits—to radiation during several phases of the process. In contrast, the solution designed for ESSOR has been conceived to operate fully remotely, minimizing personnel radiological exposure as much as possible.

Moreover, the size and complexity of the ESSOR reactor differ greatly from those of the VVR-S-60. ESSOR has a larger volume, a significantly higher number of elements to manage, and components of greater size and geometric diversity. In this context, a manual methodology like the one applied in Măgurele would be impractical: execution times would increase exponentially, and logistical and spatial requirements would render the process inefficient and operationally unfeasible.

In summary, although the Măgurele experience constitutes a valuable reference in the field of research reactor segmentation, its approaches and solutions are only partially transferable. Differences in scale, geometry, radiological inventory, and operational requirements fully justify the adoption of an automated and remote solution as proposed for ESSOR.

3. LESSONS LEARNT

3.1. Positive Outcomes

The implementation of the selected hydraulic shear cutting solution and the development of the fully integrated handling and segmentation system for the ESSOR reactor promises several positive outcomes, both from a technical and operational perspective. One of the most significant achievements would be the successful reduction of radiation exposure to personnel. The system operates under predominantly remote control, minimizing the need for workers to interact directly with activated components and supporting strict adherence to ALARA principles. This represents a meaningful improvement compared with conventional dismantling approaches applied in similar projects.

Another expected positive outcome is the minimization of secondary waste generation. Unlike thermal or hydraulic abrasive techniques, the selected mechanical cutting method does not produce aerosols, dust, or contaminated process fluids. As a result, the radiological footprint associated with segmentation activities is substantially reduced, and the subsequent waste treatment and handling processes become more efficient and predictable. Furthermore, the precise classification of cut material into multiple radiological categories allows for optimized packaging, enabling a more rational use of shielded and non-shielded storage casks and ultimately reducing overall waste volume.

From a process-management standpoint, the integration of segmentation, radiological characterization, and packaging into a single automated workflow would be highly beneficial. The modular architecture, combined with controlled transfer interfaces and containment barriers, will ensure continuous operation without requiring intermediate manual steps. This improves workflow stability, reduced downtime, and enabled predictable sequencing of tasks. All of which contribute to better schedule performance and a more reliable project execution.

Finally, the ESSOR solution demonstrates strong replicability potential. While the system is designed for the specific geometrical and radiological conditions of a channel-type reactor, the approach and methodologies used—particularly the mechanical segmentation strategy, automated waste routing, and remote-operation philosophy—can be adapted for comparable decommissioning environments. The knowledge gained strengthens European capabilities in research-reactor dismantling and serves as a reference for future projects requiring remote cutting, characterization, and material segregation under complex radiological constraints.

3.2. Challenges

Despite the successful implementation of the cutting and waste-handling strategy, several challenges are encountered throughout the development phase. One of the primary difficulties is the high variability in geometry, material composition, and radiological inventory of the ESSOR reactor internals. Unlike homogeneous structures found in many light-water reactor dismantling projects, the channel-type configuration requires tailored solutions for positioning, gripping, cutting, and characterization. This complexity increases the engineering effort needed to ensure full accessibility and reliable alignment of the cutting system with each component.

Another significant challenge is ensuring reliable and predictable remote operation. The absence of direct human intervention inside the controlled area places strict requirements on system robustness, redundancy, and fault-tolerance. Even minor misalignments or tool degradation can cause operational interruptions, and servicing the equipment inside the contaminated zone is highly constrained. Consequently, the design demands extensive pre-testing, simulation, and qualification procedures to achieve sufficient confidence before deployment.

Logistical constraints also pose difficulties. The segmentation approach requires synchronized coordination between cutting operations, waste characterization, container availability, and storage capacity. The limited physical volume of the operational space, combined with existing building infrastructure, imposes restrictions on equipment layout and movement, requiring compact, modular, and interdependent system architectures. Integrating mechanical, hydraulic, and control subsystems within these boundaries without compromising maintainability or safety proves a significant design challenge.

Additionally, uncertainties associated with the radiological inventory require conservative planning. Limited historical operational data mean that dose-rate estimates, material activation values, and contamination patterns needed to be verified progressively during execution. This iterative verification introduces schedule uncertainty and requires contingency capability within both the cutting system and operational procedures.

Finally, the project demands extensive coordination among multiple stakeholders, including regulatory bodies, dismantling contractors, safety authorities, and engineering teams. Ensuring alignment between radiological safety requirements, operational constraints, and technological feasibility requires continuous communication and adaptation, especially during critical decision phases such as final technology selection and system integration.

3.3. Beyond Technical Criteria

The choice of cutting technology in a nuclear decommissioning project depends not only on technical criteria (material type, geometry, accessibility, dose, and waste or aerosol generation) but also on the regulatory framework and the governance model in each country. In practice, the way decommissioning is organized and overseen shapes priorities and constrains which solutions are adopted.

In countries where decommissioning is managed by a state entity (a national agency or public company), there is a tendency to prioritize scalable, standardizable cutting technologies that can be replicated across multiple sites over time. This preference serves several objectives: establishing homogeneous procedures; streamlining training and qualification; maximizing the reuse of tools and fixtures across projects; and improving the traceability and auditability of operations. In this context, robust techniques with an extensive track record and low operational risk are favored—those that deliver economies of scale and clear transferability (e.g., mechanical methods such as hydraulic shears, diamond-wire sawing, or abrasive-wheel cutting, which typically generate fewer aerosols and simplify containment). The emphasis is on inter-site consistency, knowledge retention, and equipment lifecycle optimization rather than ad-hoc solutions tailored to a single site.

Conversely, in countries where the plant operator retains responsibility for decommissioning, the choice of cutting technology is often delegated to the prime contractor responsible for delivery. Selection is strongly influenced by the contractor's prior experience, equipment portfolio, workforce competencies, supply chain, and the site-specific schedule and costs. This can lead to highly optimized solutions for local conditions (e.g., thermal cutting in open, well-ventilated areas, or mechanical cutting in confined environments or where aerosols must be minimized), even though scalability across sites is not the primary objective. The advantage is greater flexibility and room for innovation; the risk is a more heterogeneous set of approaches across facilities and the need to justify licensing and regulatory acceptance on a case-by-case basis.

Under both models, the common denominators remain non-negotiable: regulatory compliance; application of the ALARA principle; waste management aligned with waste acceptance criteria; contamination control; and both radiological and conventional safety.

3.4. Key Points

The decommissioning experience gained during the design of the segmentation machine for ESSOR reactor internal components provides several valuable insights that may support future dismantling projects with similar technical or operational constraints. First, the systematic application of a multi-criteria decision methodology proved essential for selecting the most appropriate cutting technology. By evaluating safety, reliability, waste implications, operational feasibility, and radiological constraints in a structured manner, the process ensured that the final choice aligned with both technical requirements and project priorities.

Second, the decision to adopt a fully remote and integrated solution was instrumental in reducing collective dose, minimizing operational risk, and ensuring radiological containment throughout the workflow. This approach demonstrates that remote-only operation is not only achievable but also advantageous when handling highly activated, geometrically diverse reactor internals—particularly in confined environments where conventional systems, such as submerged cutting approaches, are not feasible.

Third, the minimization of secondary waste remains a key determinant in technology selection and system design. Mechanical shear cutting demonstrates clear benefits in this regard, supporting simplified waste handling and predictable conditioning strategies, while facilitating efficient long-term storage and regulatory compliance.

Fourth, early prototyping, testing, and validation of key subsystems—particularly positioning interfaces, remote handling mechanisms, and contamination control barriers—prove essential for preventing operational interruptions during field execution. The experience reinforces the importance of front-loaded engineering, mock-ups, and simulation as standard practice in complex nuclear dismantling projects.

Finally, the ESSOR project highlights that knowledge transfer from previous dismantling initiatives is valuable but must be adapted rather than replicated. Reactor-specific geometry, local infrastructure, regulatory framework, and radiological inventory define unique boundary conditions, making tailored engineering solutions indispensable. The resulting system demonstrates that flexibility, adaptability, and modular design principles are key enablers of safe and efficient decommissioning operations.

4. CONCLUSIONS

The report consolidates a structured body of knowledge on cutting and segmentation techniques for nuclear decommissioning and applies it to the particular constraints of the ESSOR experimental reactor, where highly activated, geometrically diverse internals must be dismantled in confined conditions while respecting ALARA principles and maintaining robust containment throughout operations. The comparative review and the ensuing decision methodology demonstrate that technology selection cannot be reduced to a single performance metric; it must integrate radiological protection, operational reliability, waste minimisation, and compatibility with remote handling from the outset.

Applying a multi-criteria decision analysis to candidate technologies led to the selection of hydraulic shear cutting as the primary method, owing to its balance of safety, reliability, and process cleanliness, particularly the absence of heat-affected zones and the significant reduction of aerosols and liquid secondary wastes. This decision is reinforced by operational evidence from comparable projects and by ESSOR's boundary conditions, which favour a cold, mechanically robust process capable of repeatable, remote execution over techniques that demand complex fluid management or generate substantial fumes, swarf, or slurry.

Building on that choice, the proposed solution integrates cutting, characterization, segregation, and packaging into a contained, fully remote workflow distributed across dedicated rooms with sealed interfaces. The architecture (featuring a rotary basket for controlled transfer and in-situ radiological measurement) translates the selection criteria into practical safeguards that reduce collective dose, enhance schedule predictability through automation, and maintain traceability of material streams from segmentation to cask loading. By embedding contamination control and logistics into the machine concept, the design addresses ESSOR's geometric complexity and radiological heterogeneity more effectively than simpler, single-purpose cutting arrangements.

Comparative analysis with reference cases underscores that successful decommissioning solutions are inherently site-specific. While projects such as Ågesta demonstrate effective integrated lines for more uniform components, ESSOR's channel-type configuration, wider component spectrum, and higher variability in activation demand online measurement and multi-stream segregation that cannot be achieved by replicating mobile, underwater shear campaigns or primarily manual approaches used elsewhere. The study therefore affirms adaptation over replication as a guiding principle for research-reactor dismantling.

In conclusion, the ESSOR case demonstrates that a defensible, high-performing decommissioning strategy emerges from the combination of a transparent selection framework and an end-to-end, remote, and contained operating concept. Hydraulic shear cutting, embedded within an integrated handling and characterization system, provides a pragmatic route to minimise exposure and secondary waste while maintaining throughput and control. The resulting approach is transferable in method (particularly the decision logic, containment philosophy, and remote operation model) while remaining tailored in execution to the unique geometries and radiological profiles that define each reactor.

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