LD-SAFE

Laser Dismantling Environmental and Safety Assessment

ANALYSIS OF THE DIFFERENT REACTOR COMPONENTS IN COMBINATION WITH THE SELECTION OF CONVENTIONAL CUTTING TECHNIQUES

DELIVERABLE D1.1

Reference: CN-LD-SAFE-12584-DEL-139579-EN

Number of Pages: 65

Distributed to: European Commission, ONET Technologies, CEA, IRSN, Lloyd's Register, ENGIE Solutions, TECNATOM

A	29/01/21	Initial version
Revision	Date	Description of Changes
G. GELINNE	R. VANDENDRIES	R. VANDENDRIES
Written	Reviewed	Approved

This project has received funding from the Euratom research and training programme 2014-2018, work programme 2019-2020 under grant agreement No 945255

European Commission | Horizon 2020 European Union funding for Research & Innovation

1. TABLE OF CONTENTS

2. REFERENCE

Number	Description
1	International Atomic Energy Agency, Nuclear Power Reactors in the World, IAEA Reference Data Series No. 2 (2013).
2	Toenshoff HK, Kroos F, Marzenell C. High pressure water peening – a mechanical surface strengthening process. CIRP Ann Manuf Technol. 1997;46:113-116
3	F.W. Bach, H. Steiner, G. Schreck and G. Pilot, Analysis of Results Obtained with Different Cutting Techniques and Associated Filtration Systems for Dismantling of Radioactive Metallic Components, Report EUR 14213 (1993).
4	A. Bargagliotti, L. Caprile, F. Piana and E. Tolle, Plasma Arc and Thermal Lance Techniques for Cutting Concrete and Steel, Report EUR 10402 (1986).
5	LOUIS, H., Applied Innovative Dismantling Technique: Waterjet, Proceedings of the Second Workshop Decommissioning of Nuclear Installations Technical Aspects, Doc. XII-217-99, Directorate-General XII, Mol, 1999.
6	Dismantling Techniques, Decontamination Techniques, Dissemination of Best Practice, Experience and Know-how June 2009
7	Cutting Reactor Pressure Vessels and their Internals – Trends on Selected Technologies – 10247 Nukem 2010
8	The Status and Prospect of Decommissioning Technology Development at KAERI 2019
9	REACTOR VESSEL INTERNALS SEGMENTATION EXPERIEN-CE USING MECHANICAL CUTTING TOOLS 2013
10	Westinghouse PWR and BWR Reactor Vessel Segmentation Experience in Using Mechanical Cutting Process 2016
11	Reactor Vessel Internals Segmentation Experience using Mechanical cutting tools – Technological Engineering, Volume X, number 2/2013 – ISSN 1336-5967.
12	Illustrations for PAC from Lincoln Electronic p 23-24
13	Decommissioning Study of Oskarshamn NPP Helena Larsson, Åke Anunti, Mathias Edelborg Westinghouse Electric Sweden AB June 2013

14	Dismantling of JPDR Internals Using Underwater Plasma Arc Cutting Technique Operated by Robotic Manipulator Satoshi Y ANAGIHARA, Shinsuke ASHIDAt and Hozumi USUI japan Atomic Energy Research Institute* Received August 6, 1988
15	A Study on Segmentation Process of the K1 Reactor Vessel and Internalsoung Hwan Hwang1,*, Seokju Hwang1 , Sunghoon Hong1 , Kwang Soo Park2 , Nam-Kyun Kim3 , Deok Woon Jung4 , and Cheon-Woo Kim1 1KHNP Central Research Institute, 70, 1312-gil, Yuseong-daero, Yuseong-gu, Daejeon, Korea 2Doosan Heavy Industries & Construction, 22, DoosanVolvo-ro, Seongsan-gu, Changwon, Gyeongnam, Korea 3KEPCO KPS Nuclear Power Maintenance Engineering Center, 69-46, Munsan 2 sandan 1-ro, Oedong-eup, Gyeongju-si, Gyeongsangbuk-do, Korea 4KONES #5, IL-HeungBldg., 65, Myeongdal-ro, Seocho-gu, Seoul, Korea
16	BWR Reactor Pressure Vessel Internals Segmentation and Packaging 2019 Westinghouse Electric Company LLC
17	Best practices for preparing vessel internals segmentation projects Joseph BOUCAU , Per SEGERUD , Moisés SANCHEZ a Westinghouse Electric Company, 43 rue de l'Industrie, 1400 Nivelles, Belgium
18	Mechanical cutting of irradiated reactor internals components M.G. Anderson, J.A.Fennema, MOTA Corporation
19	Assessment and management of ageing of major nuclear power plant components important to safety: PWR vessel internal, IAEA Octobre 1999, Vienna Austria
20	Evaluation Methodology of Remote Dismantling Equipment for Reactor Pressure Vessel in Decommissioning Project D. J. Hyun, B. S. Choi*, K. S. Jeong, J. H. Lee, G. H. Kim, and J. K. Moon Korea Atomic Energy Research Institute
21	Occupational ALARA Planning for Reactor Pressure Vessel Dismantling at Kori Unit 1, Department of NPP Engineering, KEPCO International Nuclear Graduate School, 658-91 Haemaji-ro, Seosaeng-myeon, Ulju-gun, Ulsan 45014, Korea

3. GLOSSARY

- ALARA : As Low As Reasonably Achievable
- AWIJ : Abrasive Water Injection Cutting
- AWSJ : Abrasive Water Suspension Cutting
- BWR : Boiling Water Reactor
- MDM : Metal Disintegration Machining
- NPP : Nuclear Power Plant
- PAC : Plasma Arc Cutting
- PWR : Pressurized Water Reactor
- REX : Return of Experience
- RPV : Reactor Pressure Vessel
- RVI : Reactor Vessel Internals

4. INTRODUCTION

One of the most challenging tasks during the dismantling of a NPP is the removal of the main components, especially the reactor pressure vessel and its internals. Thus far, several cutting methods have been applied more or less successfully for those components. However, it is still necessary to improve the performance capabilities of cutting technologies until they can cut steel more than 100 mm thick with low secondary waste generation and adaptability to a remote handling system. Moreover, to ensure worker safety against radiation exposure, it is necessary to develop a fine remote-control technology for an advanced remote handling system. The factors affecting the optimization for the selection of the decommissioning strategy are multifaceted, but safety and radioprotection must remain first and then comes the cost and time considerations of the segmentation of RVI.

5. CONTEXT OF THE PROJECT

The practice for the decommissioning of nuclear power reactors in Europe and elsewhere in the world tends to shift from deferred to immediate dismantling after permanent shutdown. This early decommissioning demand is rising on the basis of public interest and pressure from society not to pass the burden of addressing the associated legacies to future generations, in compliance with the contemporary principles of environmental sustainability and economic interest. The strategy of deferred dismantling, based mainly on the simplification of the dismantling works after long decay of the most radioactive components, does not fit in the current societal and environmental context anymore. In addition, it is increasingly admitted that immediate dismantling strategy reduces the total cost of decommissioning, both because the largest share lies in the fixed costs and because deferring involves costs for maintaining security and safety of the installation.

The global objective of the LD-SAFE project is to validate the laser cutting technology in an operational environment in-air and underwater and prove that the technology is mature to address the dismantling of the most challenging components of power nuclear reactors, that means:

- Performances and benefits validated in operational environment, taking into account the specific associated constraints.
- Compliance with the highest safety criteria as well as workers and environment protection standards and that the laser cutting technology can be included in the safety analyses of the decommissioning projects at the early stages of design.
- Reduction of the overall cost of the dismantling operations.

6. OVERVIEW OF CUTTING TECHNOLOGIES

The main objective of this chapter is to present an overview of all the common techniques of cutting the internals of a nuclear reactor. In this section we will briefly discuss the different ways of cutting metal, such as for example water jet cutting, as well as flame cutting or band saw and plasma cutting. These techniques and their comparisons are illustrated in a table in the last section of this chapter to highlight the differences between them. Further comments are then provided on the key aspects of this comparative method.

For the dismantling of the highly radioactive structures of nuclear facilities, cutting methods with much higher reliability and robustness are required compared to the dismantling of non-nuclear facilities. For this reason, various types of cutting equipment have been applied depending on the size and shape of the objects to be cut. In addition, minimizing secondary waste should be considered during the development of cutting technology. Cutting technologies for nuclear facilities can be mainly divided into three types: thermal, mechanical and hydraulic.

Thermal cutting refers to methods which separate materials by applying heat without direct contact. There are three typical thermal cutting technologies according to the type of energy source used to generate the heat: chemical (e.g., oxygen cutting), electrical (e.g., plasma arc cutting, contact arc metal processes), and laser beam cutting. These technologies are generally applicable to ferrous metals, including steel products such as sheets, plates, bars, piping, forgings, castings, and wrought iron products. Thermal cutting is, although easily adaptable to an automated process, is normally hand-held and can be performed in air or under water.

Mechanical cutting is used to separate materials by direct contact between the cutter and the objects to be dismantled, unlike thermal cutting. Typical mechanical cutting technologies include shearing, sawing, grinding, blasting, and milling. Mechanical cutting methods are generally slower than plasma arc or abrasive water jet cutting. It has been reported that specially designed circular and band saws have been developed to cut the large and thick metal structures of nuclear facilities for underwater cutting. One disadvantage of mechanical cutting is the high cost of equipment maintenance, as the cutting blades should be replaced frequently. Mechanical cutting technologies are generally stable but are also applied in a limited manner to, for instance, the end effectors of manipulators with high degrees of freedom due to the tool sizes involved.

Hydraulic cutting generally refers to methods which use fluid power without direct contact. A high-pressure fluid is sprayed onto the cut object in a narrow zone. It is easily applicable to a manipulator for precise cutting. An abrasive water injection jet (AWIJ) and an abrasive water suspension jet (AWSJ), which use abrasive materials with high-pressure water, have been applied successfully to the dismantling of nuclear facilities.

In this document we will describe the three main categories of cutting technologies. However, we will limit our analysis and will not mention laser cutting, grinding and blasting technologies. Indeed, the purpose of this document is to present the most common cutting techniques for the cutting of PWR and BWR reactor internals and to build a database in order to compare them with laser cutting.

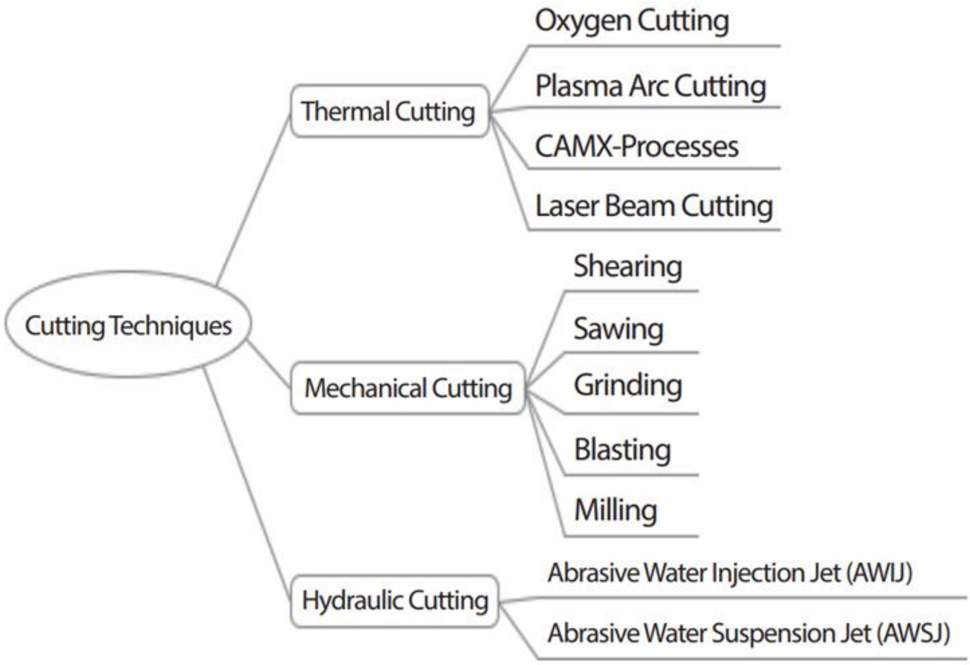

Figure 1: Classification of remote handling technologies for the decommissioning of nuclear facilities

Remote handling will have an important role to play in a dismantling project. When operation begins, it will be impossible to make changes, conduct inspections, or repair any of the components in the activated areas other than by remote handling. Very reliable and robust remote handling techniques will be necessary to manipulate and exchange components. The reliability of these techniques will also impact the choose of the technologies during the mains phases.

As mentioned above, each of the cutting techniques has some advantages and drawbacks as well. These must be weighed and evaluated prior to determining which is most appropriate. The most suitable technology among the three categories above can be selected considering the factors of the cutting efficiency, the degree of economic feasibility, and the cutting environment. We should also take into account ALARA concerns, debris management, and the reliability and projected maintenance of the equipment.

According to experience feedback, the selection of the proper cutting technology is made considering the following factors:

- Occupational safety and optimization for radiation protection,
- Secondary waste minimization,
- Process safety and simple operation,
- Reliability and maintainability,
- Cutting capacity.

Some examples of cutting techniques used in the past decommissioning projects for internals segmentation are provided hereafter:

Previous segmentation projects

Plant, Country	Reactor type	Project year	Used 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
Okiluoto 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

Figure 2 : Reactor Vessel Internals Segmentation Experience

6.1. Plasma Arc Cutting

6.1.1 Description of the technology

Plasma cutting is basically a process that is used to cut generally steel and sometimes other metals of different thicknesses. This process consists of metal melting, and then disposing of the cut metal from the slot. This is done by means of a concentrated plasma arc, having a large kinetic energy. In fact, plasma cutting uses a high temperature that prevails in the core plasma arc and high speed plasma stream. The electric arc is formed between the tungsten electrode and the cut object.

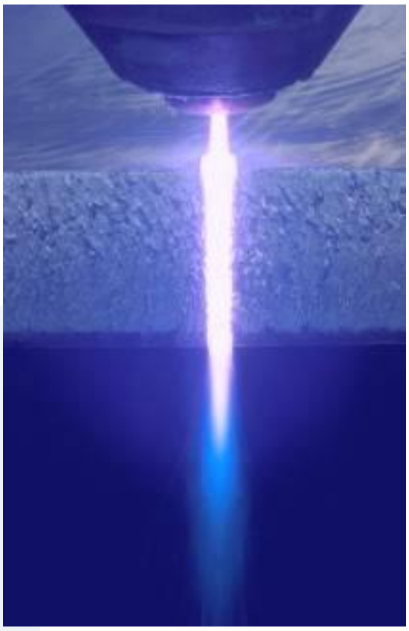

Figure 3 : Plasma cutting

A plasma cutter can pass through metals with little or no resistance thanks to the unique properties of plasma. In this section, a small explanation about state of matters is made. Due to the high temperature plasma cutting edge of a destructive influence on the confluence. This method we can usually cut up to 150 mm thick.

Further information will be provided in the fourth chapter and technical approach will be detailed.

6.1.2 Rex in Nuclear Power Plant

This technology was successfully used for remote controlled segmentation of RPV-internals from different Nuclear Power Plants in Europe and the United States. The reactor pressure vessel internals are typically cut under water. Moreover Plasma arc cutting was also already used in the dismantling of the Multi-Purpose Research Reactor in Karlsruhe.

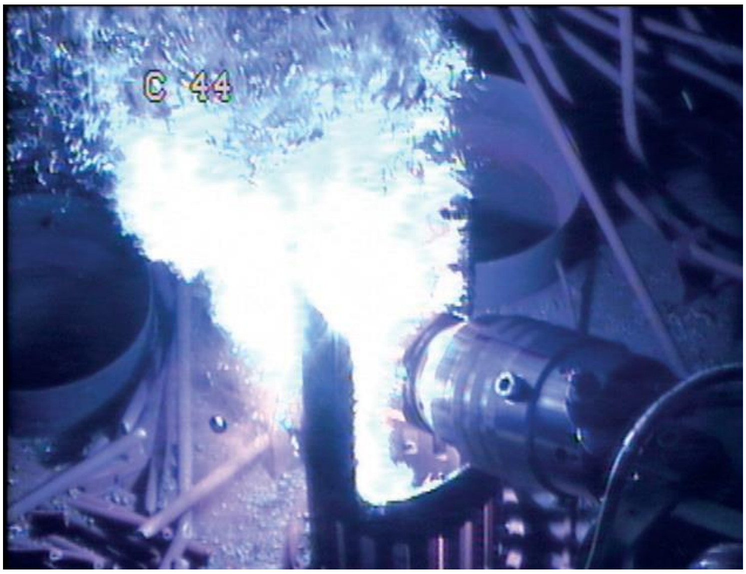

Figure 4 : Plasma arc cutting in Karlsruhe

For cutting thick materials it is necessary to create a plasma arc as long as possible. The design of the plasma torch, especially the design of the nozzle and the performance of the plasma power source, have the biggest influence on the plasma arc. General statements to the plasma torch alone are not feasible, because they are optimized for the different plasma power sources. The plasma power sources are normally standard plasma power sources for conventional cutting tasks up to 600 amps (250 volts). Therefore the reachable cutting thickness is approx. 160 mm in atmosphere and approx. 100 mm under water. The combination of three sources was used to provide up to 900 amps (280 volts) for underwater cutting tasks.

Figure 5 : Plasma power sources with control board cooling unit and supply lines

This Plasma Arc cutting equipment was used for successful cutting of the thermal shield in multi-purpose research reactor (MZFR) in Karlsruhe/Germany with up to 130 mm material thickness.

During cutting process particles (dust and aerosols) will be produced. Most of these particles have dimensions between approx. 0,085 µm and approx. 0,35 µm by cutting in atmosphere and by cutting under water. By underwater cutting approx. 0,03% of particles are aerosols, approx. 0,5% are hydrosols and approx. 99,2% are sediments. The air and water cleaning technologies have to take these facts into account.

Indeed, aerosols & particles (fumes) are the main concern associated to the use of thermal techniques such as PAC. Whatever the water cleaning technology, experience shows that it is very hard to maintain water clarity during underwater PAC (usually operators have to make regular stops because they lose the visual contact of the environment through the camera).

Plasma cutting technology was also used in contaminated premises containing the auxiliary equipment of Chooz A NPP in Chooz/France. For these cutting operations, related to the decommissioning of primary system auxiliaries, the licensee chose to use a robotic arm, which has been remotely operated with video feedback from a control room nearby. The arm could be equipped with different tools, such as plasma torch or hydraulic shear.

In terms of operational feedback, the plasma cutting technique has proven to be efficient and reliable, thus allowing the licensee to reach the decommissioning objectives in contaminated premises. In terms of safety, radiation exposure to workers has been limited, thanks to the remote operation. However, this technique required a dedicated ergonomic control room nearby, as man/machine interface is a safety key issue for controlling the robotic tool. Also, in-air plasma cutting requires ventilation and filtration systems, to prevent airborne contamination dissemination in the premises.

6.2. Abrasive Water Jet Cutting

6.2.1 Description of the technology

The technique uses a mix of water and a fine abrasive for cutting hard materials. Mix abrasives with high pressure water give an effective tool to cut metals and nonmetals materials. Abrasive water jet cutting is the most suitable process for very thick, highly reflective or highly thermal-conductive materials, laminates and composite materials, as well as hard synthetics. The abrasive stream produces a kerf width that is ideal for cutting materials.

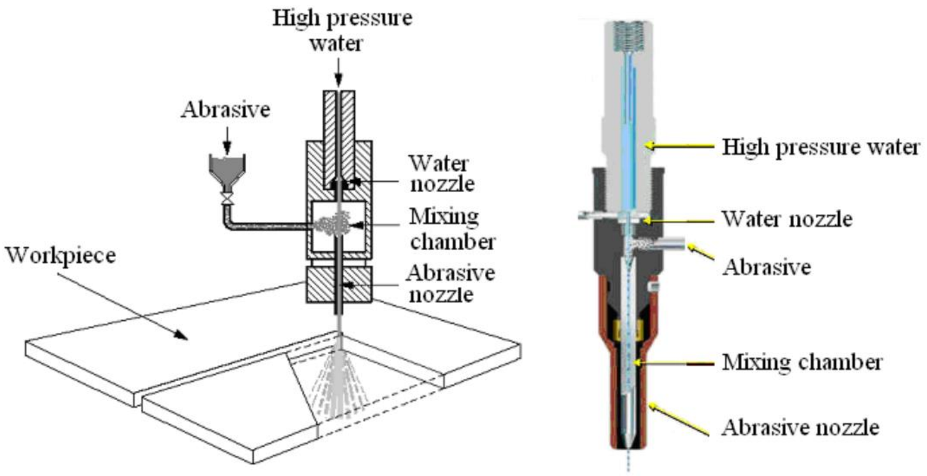

Figure 6 : Abrasive water jet cutting

Abrasive water jet can cut a wide range of thickness. Typical thickness are 100 mm for stainless steel, 120 mm for aluminum, 140 mm for stone, 100 mm for glass, but not limited. Abrasive water jet cutting is of great interest for various reasons. Almost any material can be cut. The abrasive water jet makes it possible to cut random contours, very fine tabs and filigree structures. Abrasive water jet cutting is a very precise technique. Tolerances of ±0.1 mm can be realized in metal cutting.

The workpiece is not heat-stressed. Materials cut by abrasive water jet have a smooth, satin-like finish, similar to a fine sandblasted finish. Abrasive water jet cut material at room temperatures. As a result, there are no heat-affected areas or structural changes in materials. Abrasive water jet can cut hardened metals and materials with low melting points. No heavy burrs are produced by the abrasive water jet.

6.2.2 REX in Nuclear Power Plant and relation with the internals of reactors

In nuclear engineering the practice of having multiple, redundant, and independent layers of safety systems for the single, critical point of failure is known as “defense in depth”. Even the determination of the cutting parameters may be part of a safe approach to the job. Using AWSJ the jet can still have a remarkable power behind the kerf. Thus any object behind the kerf in the range of the jet may be damaged without purpose.

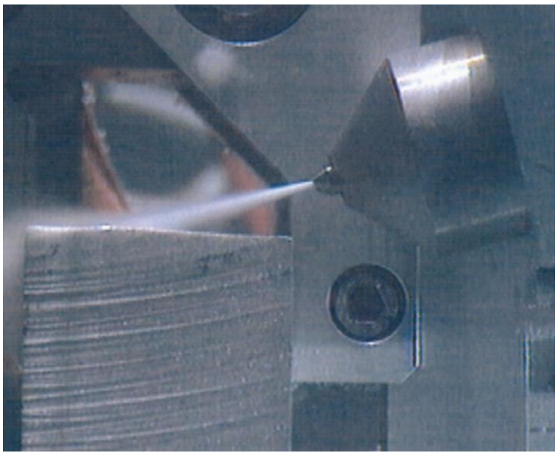

Figure 7 : Waterjet cutting used in dismantling

An example from the Versuchsatomkraftwerk Kahl (VAK), Karlstein, Germany is given below: The Thermal Shield, a cylindrical part of the reactor pressure vessel internals with 32 mm wall thickness had an outer diameter of 2390 mm, while the inner diameter of the RPV itself was 2438 mm. Thus the size of the resulting gap in between was only 24 mm. Figure 6 is a top view of this geometrical situation including the head of a suction device ("ASV"). The Thermal Shield should be cut using AWSJ.

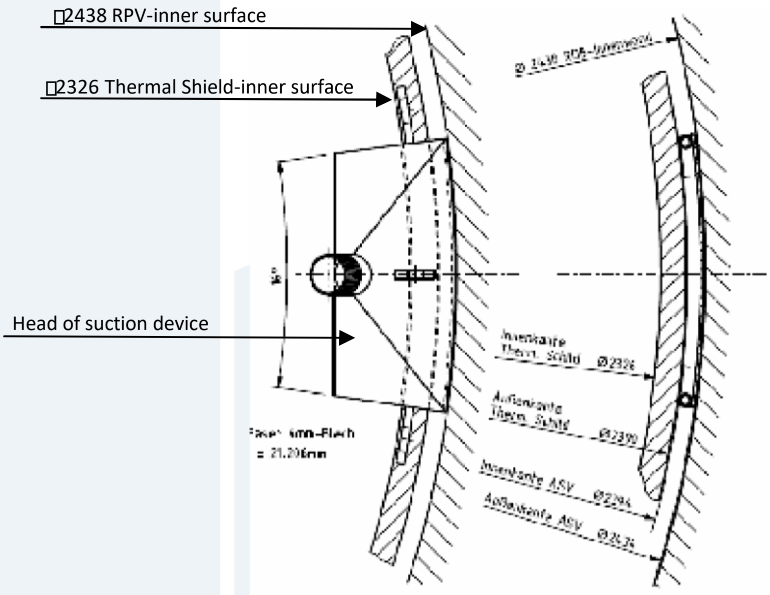

Figure 8: Geometry of thermal shield

A penetration of the stainless steel cladding on the inner surface of the RPV was seen as "the critical point of failure". Due to missing space the Thermal Shield could not be moved to another position, which would be a solution for the protection of the RPV cladding.

To protect the cladding finally two separate principles were used:

1. During Mock up testing a set of cutting parameters (speed, pressure, abrasive flow and the angle between nozzle and surface of thermal shield) was determined in such a way that during normal operation the cladding was not penetrated.
2. A protective ceramic cladding was brought into the gap between RPV and Thermal Shield. This ceramic cladding had a very high resistance to the water jet and was combined with the suction device of the water cleaning system. Thus no additional handling was required.

Using two different principles to avoid damage to the cladding was a first step towards "defense in depth" transferred from reactor design to reactor dismantling.

Some conclusions were made after the study of the technology in the nuclear field. First, the additional water and the abrasive particles will stay in the working area. It can be exhausted and disposed of in normal nuclear waste barrels or containers.

Generally the abrasive waterjet cutting technology can be used in atmosphere and under water. In atmosphere the cutting process produces strong splashes with wide contamination of hydrosols and aerosols. This has to be covered. Under water the contamination of hydrosols and aerosols are not relevant, because all particles will be captured in the water. Therefore, large piece of underwater systems are set up to deliver, recover and recycle the abrasive shot.

Behind the cut kerf, the water jet is still so powerful that it can cut or damage other material in its range. This fact must be considered during planning the cutting strategy.

Abrasive water jet cutting has been used also for Rancho Seco Vessel Segmentation (Cf Rancho Seco Reactor Vessel Segmentation Experience Report EPRI 2008) and for the Main Yankee reactor vessel internals (Cf. Main Yankee Decommissioning experience Report Detailed experiences 1997-2004). One of the main lessons learnt is the combination of a highly designed robotic manipulator with abrasive water jet cutting proved to be very effective in achieving the needed precision in the vessel cutting project. In addition, processing of garnet waste must be given considerable attention due to the garnet size reduction resulting from cutting of thick walled pieces (9-11 inches, 22,9-27,9 cm). At Main Yankee, The most difficult challenge in the internals segmentation process was the removal of the colloidal suspension created from the fragmentation of the garnet used in the abrasive water jet cutting. In addition, a new licensed waste container for the high level abrasive swarf has been developed.

The AWJC process has been used at SONGS 1 located in San Onofre, California, USA. It has been observed that Abrasive water jet cutting leaves a very narrow kerf (less than one millimeter in width), allowing a minimum of activated metal to be released during the cutting operation. The omnidirectional cutting ability makes AWJC extremely versatile for segmentation of complex geometries and limited-access cut locations. This process led to high cost for process control and disposal of highly irradiated secondary waste (Cf Reactor Vessel Internals Segmentation Experience using Mechanical cutting tools - Technological Engineering, Vomue X, number 2/2013 - ISSN 1336-5967).

6.3. Band Saw

6.3.1 Description of the technology

Band saw cutting is the most widely used method for dismantling nuclear facilities. Band sawing uses a continuous flat blade that rides around a set of coplanar pulleys, one of which is driven by motor. The driven pulley drives the blade through contact friction between the pulley and the blade. The other pulleys are idler pulleys that provide tension in the blade. A flat section of blade is usually supported by hardened slotted guides. This area contacts the workpiece and is where the cutting takes place. The blade is made from special tool steel and has multiple teeth on one edge that repeat in a pattern over the entire length. The size, shape and tooth pattern are available in a variety of combinations for different workpiece materials and applications.

Band saw machines with a swing frame:

The simplest and most common form are saws with a swing frame. A common area of application for this type of saw is the subsequent dismantling of components for the purpose of packaging and in preparation for subsequent conditioning steps. Thanks to their simple design, they can be used at relatively low cost.

Figure 9 : Band saw with swing frame

Band saw with a dual-column guide:

A widely used field of application for this type of saw is the dismantling of large reactor components. The dual-column saw has special guide systems for this purpose and carries out its separation tasks directly within the reactor cavity. The components to be separated are significantly larger than the band saw itself. Stainless steel versions of this type of saw are well suited for use under water.

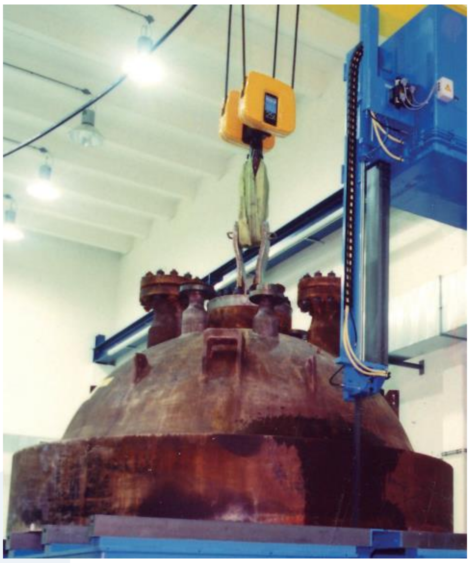

Figure 10 : Band saw with a dual-column guide

6.3.2 REX in Nuclear Power Plant

Band saw cutting is a slow but sturdy and reliable mechanical tool that has been used at decommissioning sites such as research reactors TRITON, ATTILA and EL3. For the TRITON site, a saw was used underwater to cut the core grid without contaminating the 800 m3 of water in the reactor pool, allowing it to be released without further treatment. This technique has been used in the reactor internals decommissioning of Chooz A NPP in Chooz/France. For these operations, the licensee chose to use underwater cutting techniques for the vessel internals, including band sawing. Operations were remotely controlled from a footbridge above the reactor pool, where workers could operate equipment, with direct view or remote video monitoring, on the equipment to be dismantled.

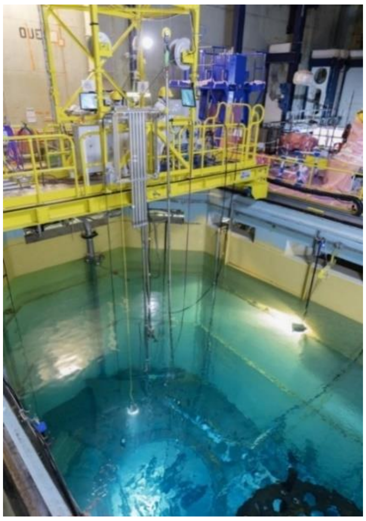

Figure 11 : Footbridge above reactor pool for reactor internals decommissioning control

In terms of operational feedback, band sawing allowed the licensee to dismantle the reactor vessel internals accordingly to the schedule.

From a safety perspective, these operations have proven to be efficient, reliable and flexible. Especially, waste has been cut into pieces, in compliance with the size allowed for conditioning in the required package. Water turbidity and specific activity were controlled with filtering systems (filters and ion exchange resins).

However, this process led to the production of liquid discharges as well as secondary waste generation (water filters). Internal contamination (not exceeding regulatory dose limits) of some workers have also been reported in 2017 during these operations.

As another example, the José Cabrera upper core Barrel was segmented using a band saw on a centre pillar. The segmentation strategy was to perform a number of vertical cuts, drill a hole at the end of one cut, turn the blade 90 degrees, cut a 360 degree horizontal cut and removing the pieces that comes lose one by one. Mechanical cutting provides benefits in terms of secondary waste volume and water clarity. Cutting speed is lower than for the Plasma Arc or AWJ.

6.4. Circular Saw

6.4.1 Description of the technology

Thanks to their housing designs, circular saws are especially well-suited for use in limited spatial environments.

Circular saw with a swing frame:

The main area of application for this type of saw is the subsequent cutting of components. Due to their simple design, they are very inexpensive, and provide a high level of technical reliability at the same time.

Circular saw with a linear drive :

Circular saws with linear drives are used for nuclear decommissioning especially for separating larger components into sections. In comparison to a circular saw with a swivel arm, they have a much larger operating area and can therefore be used more flexibly. Stainless steel versions are also suitable for cutting under water.

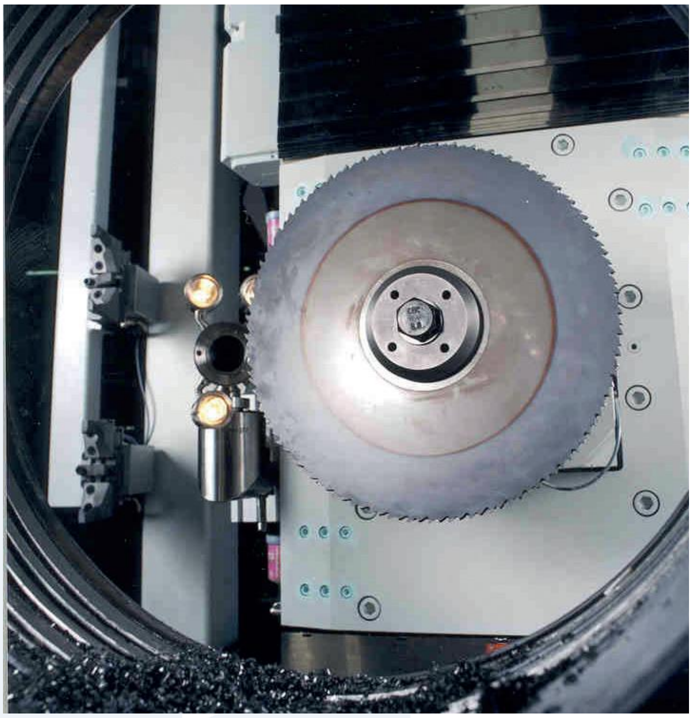

Figure 12 : Circular saw

6.4.2 REX in Nuclear Power Plant

The main feedback of the technology are the high force feedback know to damage robotic arms in remote and the risk of blockage on the blade in the cut piece. It should be noted that the replacement of discs due to wear is to be taken into account during a cutting operation using this technology.

6.5. Milling Cutters

6.5.1 Description of the technology

The areas of application for milling cutters are varied, however, compared to saws, milling cutters are not connected to a linear cutting guide. Different kinds of specific saw kerfs can be made. Therefore, milling is well suited, for example, to the targeted removal of welds or other joints. Two different types of milling cutter are used for dismantling.

Figure 13 : milling cutters

End milling cutters:

These end milling cutters are made of high-speed steel material or carbide inserts. The kerf is produced by rotating the cutter while simultaneously being fed into a tool axis. The component is fed in until it is cut through completely. The cutter length determines the limits of the cutting depth and is approximately 30 mm. The special advantage of end milling cutters as a separation technique is the high level of flexibility of the kerf form.

Side milling cutters:

While end milling cutters produce relatively wide kerfs, the advantage of side milling cutters is that they produce a relatively narrow kerf. However, this can only be carried out as a straight kerf.

Cutting speed is defined as the speed at the outside edge of the tool as it is cutting. This is also known as surface speed. Cutting speeds depend primarily on the kind of material you are cutting and the kind of cutting tool you are using. The hardness of the work material has a great deal to do with the recommended cutting speed. The harder the work material, the slower the cutting speed.

Type of Material	Cutting Speed (SFM)
Low Carbon Steel	40-140
Medium Carbon Steel	70-120
High Carbon Steel	65-100
Free-machining Steel	100-150
Stainless Steel, C1 302, 304	60
Stainless Steel, C1 310, 316	70
Stainless Steel, C1 410	100
Stainless Steel, C1 416	140
Stainless Steel, C1 17-4, pH	50
Alloy Steel, SAE 4130, 4140	70
Alloy Steel, SAE 4030	90
Tool Steel	40-70
Cast Iron–Regular	80-120
Cast Iron–Hard	5-30
Gray Cast Iron	50-80
Aluminum Alloys	300-400
Nickel Alloy, Monel 400	40-60
Nickel Alloy, Monel K500	30-60
Nickel Alloy, Inconel	5-10
Cobalt Base Alloys	5-10
Titanium Alloy	20-60
Unalloyed Titanium	35-55
Copper	100-500
Bronze–Regular	90-150
Bronze–Hard	30-70
Zirconium	70-90
Brass and Aluminum	200-350
Silicon Free Non-Metallics	100-300
Silicon Containing Non-Metallics	30-70

Figure 14 : Cutting speed of milling cutters (surface feet per minute)

6.5.2 REX in Nuclear Power Plant

Milling cutter has been used for under water cutting works at Greifswald. During this dismantling project, a mix of several cutting techniques were used. For the pre-cutting station, a high power band saw will be used. With this equipment, the pressure vessel as well as the upper part of the protecting tube system and reactor cavity will be cut horizontally into sections. For the wet cutting area there are a number of underwater techniques that will be used which include: high power vertical band saw, abrasive cutting machines, shears, milling cutter.

The decision for the use of a milling machine to cut the reactor vessel was based on a multiplicity of restrictions and circumstances that greatly reduced the range of potential cutting techniques:

- No wet or thermal cutting techniques allowed, because of the sodium residues.
- Restricted space in the vessel (diameter 2m).
- Complex geometry of the built-in components (for instance reflector, grid plate).
- High material thickness of single components (reflector).

The internals of the reactor vessel had to be dismantled from the inside out. The inner vessel and the outer vessel had to be removed top down because they were suspended from the top flange.

6.6. Flame Cutting

6.6.1 Description of the technology

Flame cutting is a thermal cutting process for separating components made of construction steel. This method is used mainly for separating thick-walled components, such as a reactor pressure vessel. The necessary process gases oxygen, acetylene or propane are supplied via flexible hose lines to the oxy-fuel torch. With this relatively small burner, it is possible to flexibly separate components with complex geometries. The resulting process forces are very small, so that the mechanical requirements of the guide systems can also be relatively low. Overall flame cutting is therefore a very cost-effective technology.

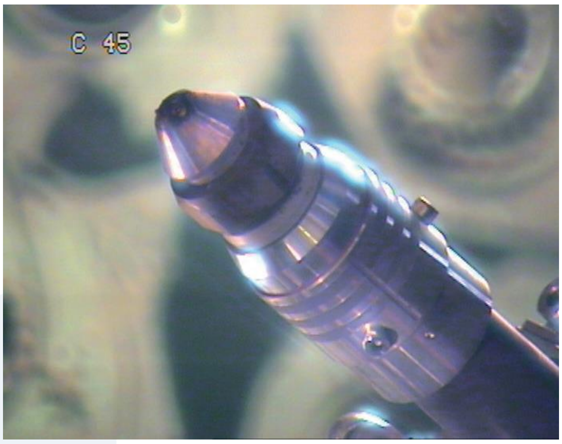

Figure 15 : Flame cutting

Flame cutting has the advantage of being very portable as no power supplies are needed. A cylinder for oxygen, a cylinder for fuel gas, hoses, a torch, and a striker are all that are required. This makes it an excellent choice for field work. Another benefit of flame cutting is that it can cut very thick metals. With the right equipment and gas flows, steel several feet thick can be cut using the flame cutting process. Flame cutting also has low equipment costs.

Flame cutting is at a disadvantage when it comes to material types that can be cut. Flame cutting is generally limited to carbon steel, low alloy steels, and cast irons. Most other types of materials will not be cut cleanly by the flame cutting process. Flame cutting is also typically slower than plasma cutting and waterjet cutting.

6.6.2 REX in Nuclear Power Plant

Flame cutting is commonly used in dismantling of small facilities because of its flexibility. However, it does not require primary power, nor compressed air. Therefore, it is easily portable. The 15 kg set allow cut metal pretty much anywhere, making it a solution for on-site cutting jobs.

The technology was used for RPV dismantling in Germany but in general rarely used in teleoperation in the nuclear sector even if it is not a limitation in the use of the technique.

6.7. Contact Arc Metal Cutting

6.7.1 Description of the technology

Contact Arc Metal Cutting (CAMC) is a thermal cutting technology for underwater cutting tasks of all electric conductive materials, developed in the last two decades. The structure of the components which will be cut is not relevant. Gaps and hollow structures are not a problem.

Contact-Arc-Metal-Cutting with a sword like cutting-electrode is a thermal cutting technique currently used for decommissioning of nuclear facilities. A water jetting electrode made up of pure graphite, carbon fiber reinforced graphite or a special tungsten-copper-alloy, melts the metallic work piece in a cyclic process by resistance heating and a free burning high current spark channel. These arcs have a strong thermal effect and can melt all metallic materials. Consumption of the electrode, however, is low. A supporting flow of water along the electrode carries the molten metal away. When the electrode is moved in the direction of cut, a kerf is formed. Graphite or metal are both possible materials for the electrode One advantage of using graphite is that the electrode cannot get stuck in the kerf because it cannot weld itself to the workpiece. A Master-Slave-Manipulator leads the electrode through the components, free of tool guiding force. Therefore, the manipulator may be designed relatively simple. With CAMC, all electrically conductive materials can be cut, including stainless steel plated mild steel constructions. The maximum component thickness that can directly be cut depends on geometry of the electrode and the efficiency of the water scavenging.

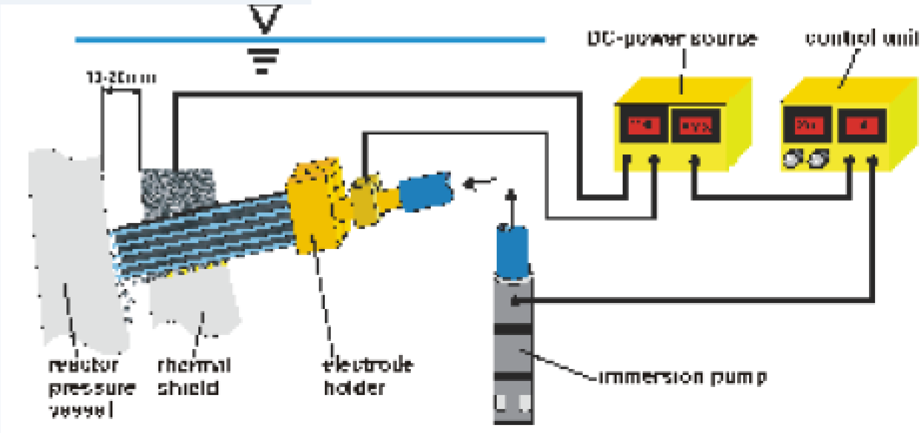

Figure 16: CAMC principle

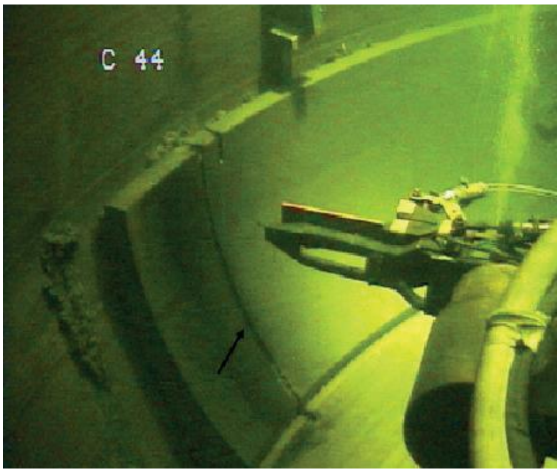

Figure 17: CAMC used to dismantle nuclear facilities

6.7.2 REX in Nuclear Power Plant

CAMC was already used in the dismantling of the Multi-Purpose Research Reactor in Karlsruhe. His process control optimizes the feed motion depending on the resistance heating and the free burning high current spark channel. A special CAMC-tool with a turntable drive unit and an integrated process control for automatically cutting was developed by scientists of the Institute of Materials Science of Hanover.

6.8. Qualitative comparison

In this study, relevant factors have been identified for describing the cutting technique, integrated and tabulated the qualitative data from a number of research papers and reports. Therefore, this paper have investigated wider technologies and more factors and analyzed them with 6 factors. Those are possibility of underwater work, cutting object (material and shapes including cutting depth), cutting speed, cost, required space and ease of work and secondary waste generation. The results are shown in Table 1.

	Thermal cutting technologies			Mechanical cutting technologies			Hydraulic cutting technologies
Technologies	**Plasma cutting**	**Flame cutting**	**Contact arc metal cutting**	**Circular saw**	**Band saw**	**Milling cutters**	**Abrasive water jet cutting**
Field of application	in air / underwater	in air / underwater	in air / underwater	in air / underwater	in air / underwater	in air	underwater
Shape	1) Large diameter pipes and tanks, plate and pressure vessels 2) Adaptability to various shapes	1) Large diameter pipes and tanks, plates and pressure vessels, shafts, beams 2) Simple shapes	Small diameter pipes, plates and pressure vessels	Complicated shapes Small diameter pipes	1) Thick structures and wall or floor (<60cm) 2) Pipes, Metal	Simple shapes	Complicated shapes
Materials	Electrically conductive material	Objects with low thermal conductivity	Electrical conductive materials	All materials	All materials	All materials	All materials
Cutting speed (mm/min)	1) Fast 2) Slower underwater	1) Fast 2) Slower underwater	Slow	Slow	Slow	Slow	Medium
Cost CAPEX	Medium	Low	Medium	Medium	Medium	Low	High
Required space (remote handling)	Ventilation and water treatment 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	Ventilation and separate device for extra high-pressure water formation required
Secondary waste	1) Working gas (N2, inert gas) 2) Slag / sludge radiation particles of more about 5 times compare to mechanical cutting 3) Large amounts of contaminated aerosols	1) Ferritic oxide (slug) 2) Fumes	About 5 times the mechanical cutting	No flame generation, few aerosols	No flame generation, no radioactive contamination such as smoke or gas	No flame generation, no radioactive contamination such as smoke or gas	1) Used abrasive post-treatment required 2) Few air pollution 3) Water

Safety advantages	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 (under water)	Limitation of airborne contamination (in air) or water contamination (under water)	No airborne contamination
Safety drawbacks	1) Need to address fire hazard and airborne contamination (in air) 2) Need to address radiation protection in the vicinity of filtering systems 3) Contamination of water with small particles (under water)	1) Need to address fire hazard and airborne contamination (in air) 2) Need to address radiation protection in the vicinity of filtering systems 3)Contamination of water with small particles (under water)	1) Need to address fire hazard and airborne contamination (in air) 2) Need to address radiation protection in the vicinity of filtering systems 3) Contamination of water with small particles (under water)	N/A	N/A	1) Not convenient for adapting cutting pattern to waste package size	N/A

Table 1 : Performance characteristics of metal cutting technologies

7. COMPARISON OF MAIN SOLUTIONS FOR CUTTING INTERNALS

In this chapter, we will go into details to highlight the three mains technologies to cut internals of nuclear reactor. The chosen technologies mainly used in dismantling are plasma arc cutting, abrasive water jet and band saw cutting. The goal of this chapter is to provide a technical approach of the technologies and how it is possible to cut the internals of the reactor.

7.1. Plasma Arc Cutting: a technical approach

As mentioned before, plasma is an electro thermal cutting process. Due to its operational flexibility and high cutting speed, plasma cutting has become one of the standard methods for separating metallic components. Plasma cutting, is a processing method that uses the heat of a high-temperature plasma arc to locally melt and evaporate the metal at the cut of the work piece, and uses the momentum of high-speed plasma to remove the molten metal to form the cut.

7.1.1 Definition of plasma

The first three states of matter are solid, liquid and gas (Figure 18) . For the most commonly known substance, water, these states are ice, water and steam. If you add heat energy, the ice will change from a solid to a liquid, and if more heat is added, it will change to a gas (steam). When substantial heat is added to a gas, it will change from gas to plasma, the fourth state of matter.

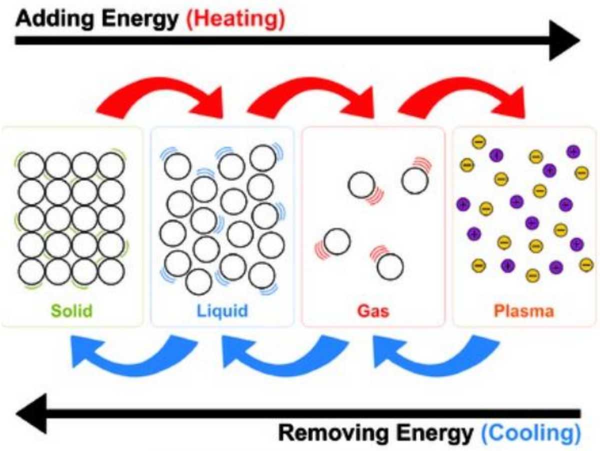

Figure 18 : States of matter

Plasma is an electrically conductive gas. The ionization of gases causes the creation of free electrons and positive ions among the gas atoms. When this occurs, the gas becomes electrically conductive with current carrying capabilities. Thus, it becomes a plasma.

7.1.2 Description of the full cutting system

The plasma cutting process, as used in the cutting of electrically conductive metals, utilizes this electrically conductive gas to transfer energy from an electrical power source through a plasma cutting torch to the material being cut.

The basic plasma arc cutting system consists of a power supply, an arc starting circuit and a torch. These system components provide the electrical energy, ionization capability and process control that is necessary to produce high quality, highly productive cuts on a variety of different materials.

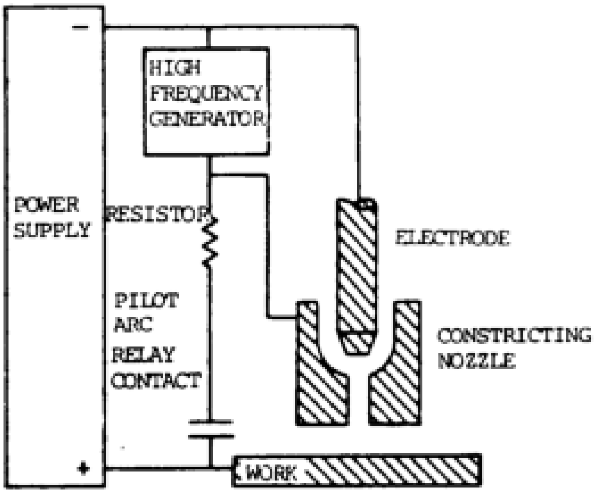

Figure 19 : Basic arc plasma principle

The power supply is a constant current DC power source. The open circuit voltage is typically in the range of 240 to 400 VDC. The output current (amperage) of the power supply determines the speed and cut thickness capability of the system. The main function of the power supply is to provide the correct energy to maintain the plasma arc after ionization.

The arc starting circuit is a high frequency generator circuit that produces an AC voltage of 5,000 to 10,000 volts at approximately 2 megahertz. This voltage is used to create a high intensity arc inside the torch to ionize the gas, thereby producing the plasma.

The torch serves as the holder for the consumable nozzle and electrode, and provides cooling (either gas or water) to these parts. The nozzle and electrode constrict and maintain the plasma jet.

The power source and arc starter circuit are connected to the torch via interconnecting leads and cables. These leads and cables supply the proper gas flow, electrical current flow and high frequency to the torch to start and maintain the process.

Laser Dismantling Environmental and Safety Assessment

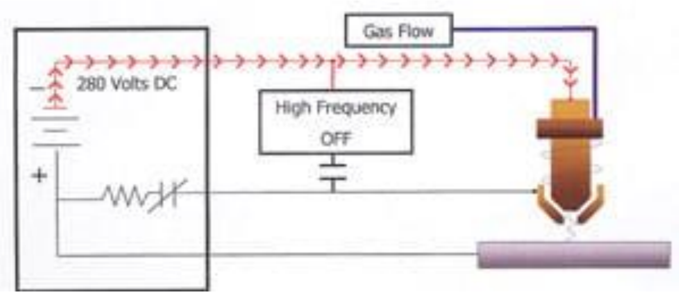

Figure 20 : Basics of plasma cutting (1)

A start input signal is sent to the power supply. This simultaneously activates the open circuit voltage and the gas flow to the torch. Open circuit voltage can be measured from the electrode (-) to the nozzle (+). Notice that the nozzle is connected to positive in the power supply through a resistor and a relay (pilot arc relay), while the metal to be cut (work piece) is connected directly to positive. Gas flows through the nozzle and exits out the orifice. There is no arc at this time as there is no current path for the DC voltage.

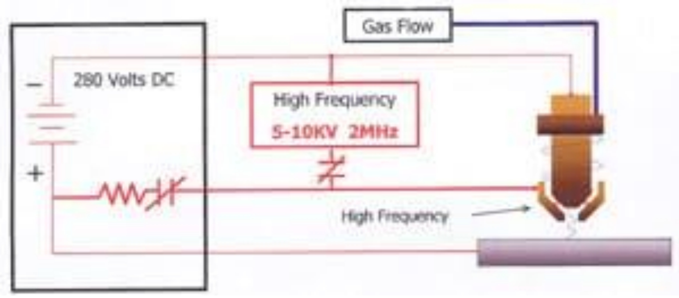

Figure 21 : Basics of plasma cutting (2)

After the gas flow stabilizes, the high frequency circuit is activated. The high frequency breaks down between the electrode and nozzle inside the torch in such a way that the gas must pass through this arc before exiting the nozzle. Energy transferred from the high frequency arc to the gas causes the gas to become ionized, therefore electrically conductive. This electrically conductive gas creates a current path between the electrode and the nozzle, and a resulting plasma arc is formed. The flow of the gas forces this arc through the nozzle orifice, creating a pilot arc.

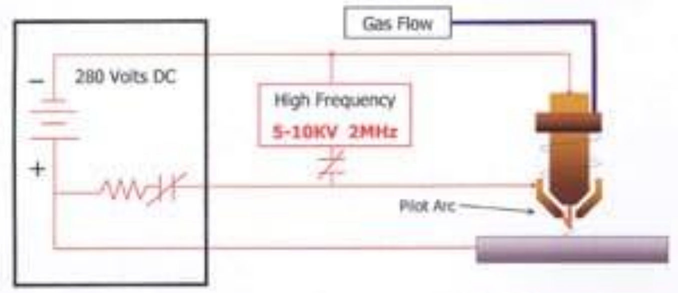

Figure 22 : Basics of plasma cutting (3)

Assuming that the nozzle is within close proximity to the work piece, the pilot arc will attach to the work piece, as the current path to positive (at the power supply) is not restricted by a resistance as the positive nozzle connection is. Current flow to the work piece is sensed electronically at the power supply. As this current flow is sensed, the high frequency is disabled and the pilot arc relay is opened. Gas ionization is maintained with energy from the main DC arc.

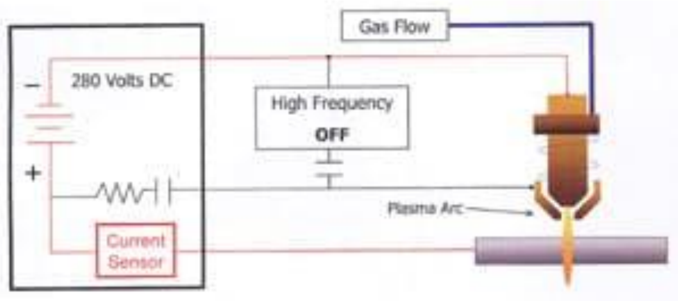

Figure 23 : Basics of plasma cutting (4)

The temperature of the plasma arc melts the metal, pierces through the work piece and the high velocity gas flow removes the molten material from the bottom of the cut kerf. At this time, torch motion is initiated and the cutting process begins.

7.1.3 From the plasma nozzle

Accurate cuts can be made in stainless steel and non-ferrous metals such as aluminum by plasma arc cutting. The cuts are made by a high temperature, high velocity gas jet generated by constricting an arc between a tungsten electrode and the component. The heat from the arc melts the metal and the gas jet removes the molten metal from the cut. The arc operates in an inert inner shield, whilst an outer shield provides protection for the cut surface. Argon, helium, nitrogen and mixtures of these gases are used for both the inner and outer shields. Plasma arc cutting is characterized by fast cutting speeds and is mainly used in mechanized systems. The cutting is accompanied by a high noise level which can be reduced by operating the torch under water.

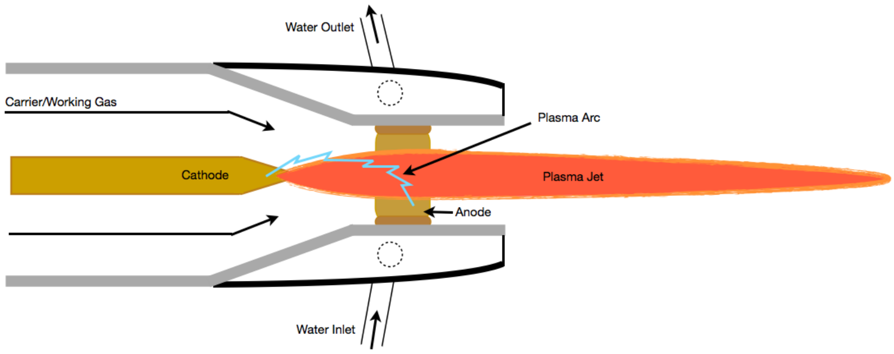

Figure 24 : Plasma nozzle

Plasma cutters work by sending a pressurized gas, such as nitrogen, argon, or oxygen, through a small channel. In the center of this channel, you'll find a negatively charged electrode. When you apply power to the negative electrode, and you touch the tip of the nozzle to the metal, the connection creates a circuit. A powerful spark is generated between the electrode and the metal. As the inert gas passes through the channel, the spark heats the gas until it reaches the fourth state of matter. This reaction creates a stream of directed plasma.

The plasma itself conducts electrical current. The cycle of creating the arc is continuous as long as power is supplied to the electrode and the plasma stays in contact with the metal that is being cut. In order to ensure this contact, protect the cut from oxidation and regulate the unpredictable nature of plasma, the cutter nozzle has a second set of channels. These channels release a constant flow of shielding gas around the cutting area. The pressure of this gas flow effectively controls the radius of the plasma beam.

Inside a precision plasma torch, the electrode and nozzle do not touch, but are isolated from one another by a swirl ring which has small vent holes that transform the plasma gas into a swirling vortex. When a start command is issued to the power supply, it generates up to 400VDC of open circuit voltage and initiates the gas through a hose lead set to the torch. The nozzle is temporarily connected to the positive potential of the power supply through a pilot arc circuit, and the electrode is at a negative.

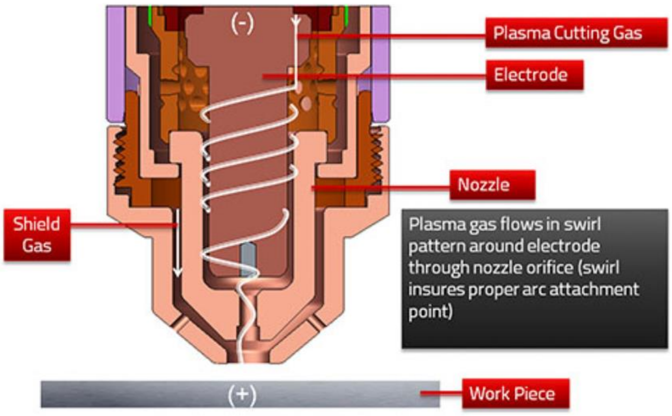

Figure 25: Plasma cutting principle (1)

Next, a high frequency spark is generated from the Arc Starting Console which causes the plasma gas to become ionized and electrically conductive, resulting in a current path from electrode to nozzle, and a pilot arc of plasma is created.

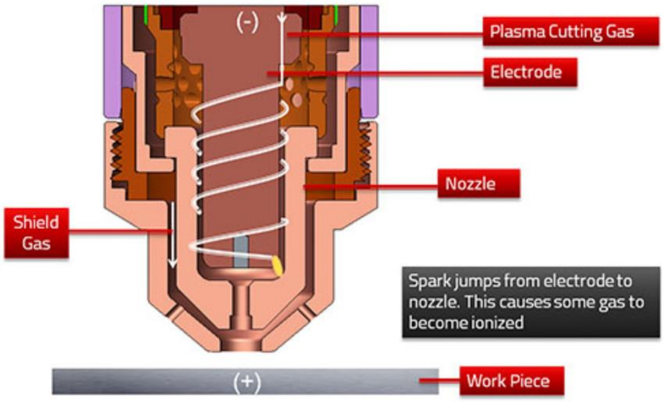

Figure 26 : Plasma cutting principle (2)

Once the pilot arc makes contact to the work piece (which is connected to earth ground through the slats of the cutting table), the current path shifts from electrode to work piece, and the high frequency turns off and the pilot arc circuit is opened.

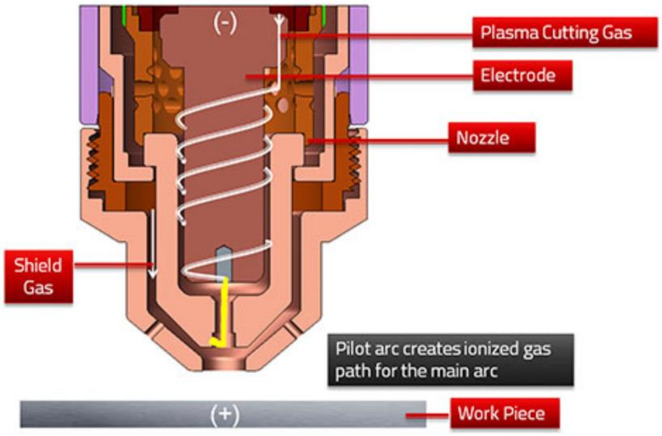

Figure 27 : Plasma cutting principle (3)

The power supply then ramps up the DC current to the cutting amperage selected by the operator and replaces the preflow gas with the optimum plasma gas for the material being cut. A secondary shielding gas is also used which flows outside of the nozzle through a shield cap.

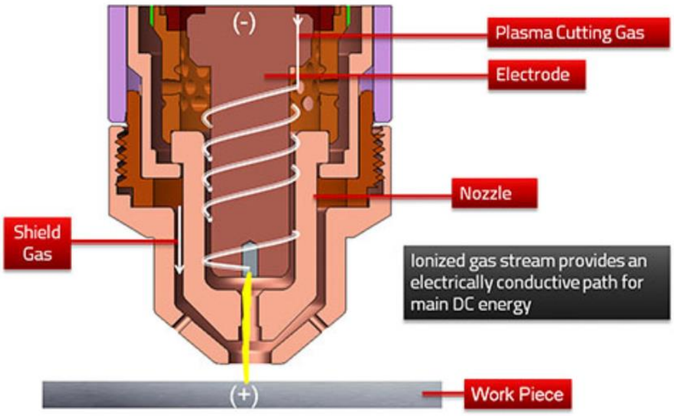

Figure 28 : Plasma cutting principle (4)

The shape of the shield cap and the diameter of its orifice forces the shield gas to further constrict the plasma arc, resulting in a cleaner cut with very low bevel angles and smaller kerf.

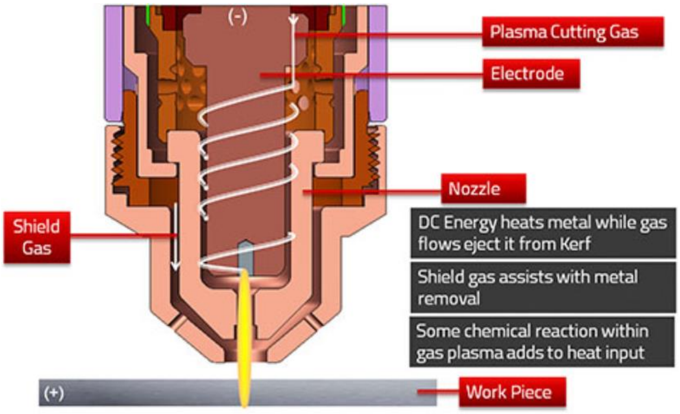

Figure 29 : Plasma cutting principle (5)

7.1.4 Selection of the correct gas

The cutting gas selected depends on the speeds and quality of cut desired. Several cutting gases can be used in a plasma system to improve cut quality and speed. Nitrogen is widely used because it is relatively inexpensive and can be used on many materials and thicknesses. Special mixtures of argon and hydrogen can improve cutting speed and quality on thicker metals and those other than carbon steels. Oxygen is used in combination with other gases to improve cut quality by increasing heat, improving cutting speed, and/or reducing power requirements. Compressed shop air is popular for many applications because it is inexpensive and provides good quality cuts on thicknesses under 25mm, especially on carbon steels.

Gas quality is critical for the proper operation of plasma arc cutting systems and optimal cut quality. Any contaminates can cause misfiring, poor cut quality or poor consumable life. Contaminates can be: gas impurities, moisture, dirt, piping system contaminates or improper gases.

The table below gives a list of the typical gases used for Plasma Arc cutting and the application that they are suitable for:

Gas Selection Chart			
System	Material	Plasma Gas	Shield Gas
HyDefinition	Mild Steel	O_2	O_2 & N_2
	Stainless Steel-	Air	Air
	up to ¼"	Air	Air & Methane
	above ¼" above ¼"*	H35 & N_2	N_2
	Aluminium	Air	CH_4
	up to ⅜" up to ½"	H35 & N_2	N_2
	Copper	O_2	O_2 & N_2
MAX200 & HT2000	Mild Steel	O_2	Air
	Stainless Steel	Air	Air
	up to ¼" above ½"	H35	N_2
	Aluminium	Air	Air
	Copper	O_2	Air
HT4001	Mild Steel **	O_2	H_2O
	Stainless Steel	N_2	H_2O
	Aluminium	N_2	H_2O
*Only valid if equipped with six channel gas console (p/n: 078059 & 078061). **O_2 cutting is only for 340 amps maximum. Must use N_2 for higher current.			

Figure 30 : Gas selection for plasma cutting

7.1.5 Cutting speed for plasma arc cutting

For a given electric power and gas mixture, there is an optimum speed range for each type and thickness of material. Excess speed causes a decreased kerf width with an increased bevel but current intensity is the main factor determining kerf width.

Material	Thickness mm	Current amps	Cutting speed Mm/min	Gas
Aluminium	1.5	40	1200	A/H_2
	5.0	50	1500	A/H_2
	12.0	400	3750	A/H_2
	25.0	400	1250	A/H_2
Stainless steel 18/8	2	50	1600	A/H_2
	5	100	2000	A/H_2
	12	380	1500	A/H_2
	25	500	625	A/H_2

Figure 31 : Cutting speed for plasma arc cutting

For a secure process it must be ensured that no hydrogen-oxygen reaction can occur. Therefore the volumetric hydrogen concentration in the air above the water surface has to be kept below 4,1%. Generating 12 dm^3/min of hydrogen the minimum required exhaust air flow would only be 18 m^3/h to ensure a maximum of 4,1% hydrogen concentration in the exhaust air. This can easily be ensured using a well dimensioned state of the art exhaust system and for additional security an integrated hydrogen sensor. An interlock between exhaust air system and cutting process is recommended due to control and safety reasons.

7.2. Abrasive Water Jet: a technical approach

Water jet is the method consisting of cutting the material by the use of thin water jets under high pressure with added abrasive slurry used to cut the target material by means of erosion. More specifically, waterjets can be divided into pure and abrasive subcategories. The term "pure waterjet" refers to cutting tools that use only water, while the term "abrasive waterjet" or sometimes just "abrasive jet" refers to waterjets that use an abrasive to accelerate the cutting process. Indeed, in order to improve the performance of the process additive is used in the form of abrasive grains of garnet, which allows cutting of very hard materials.

- Pure waterjet is used for cutting softer materials, including gasket, foam, food, paper, plastic and carpet. Water is pressurized to ultra-high pressure levels and forced through a small ruby, sapphire or diamond orifice to form an intense cutting stream. The jet stream moves at a velocity of up to 2.5 times the speed of sound, creating the ability to cut at very high feed rates.
- Abrasive waterjet is ideal for cutting any material in sheet or slab form including mild and stainless steel, aluminum, sheet metal, composites, decorative stone, synthetic ceramics and glass.

Basically two systems of abrasive water jets, differing in their generation, their properties and their application fields have been developed. The fundamental difference is the point of time of the abrasive addition leading to the specific jet properties. Abrasive Water Injection Jets (AWIJs) are generated by a water jet, passing through a mixing chamber and re-entering a focusing tube. This creates a low pressure in the chamber, which is used for the pneumatic transport into it. There the abrasive material is accelerated by the water jet and focused in the secondary focusing tube.

Abrasive Water Suspension Jets (AWSJs) however are characterized by the fact of the admixture of abrasive material and water takes place before the nozzle. This has the effect that contrary to AWIJs the jet only consists of water and abrasive material.

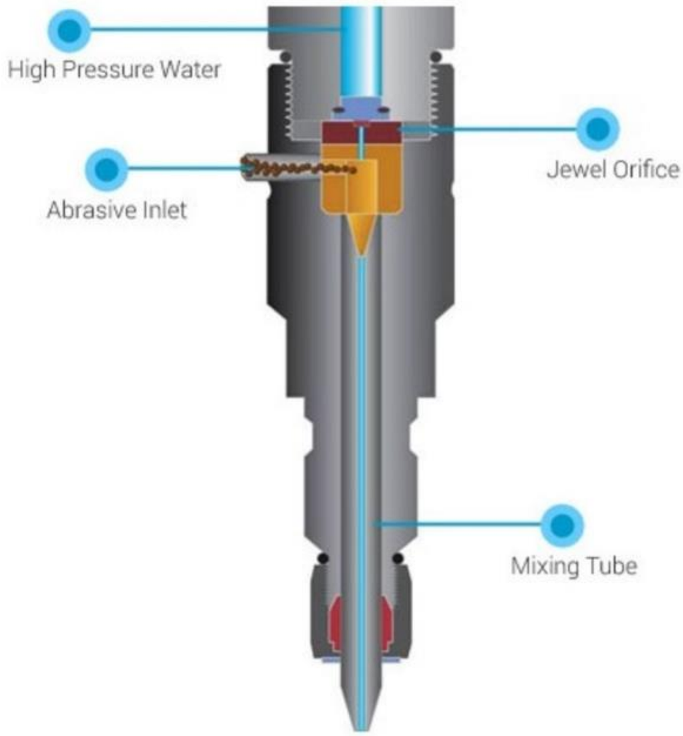

Figure 32 : Abrasive water jet cutting principle

In this section we will focus on waterjet abrasive due to the fact that is more suitable for cutting the internals of a reactor.

7.2.1 Principle of waterjet abrasives

Waterjet abrasives are typically made of garnet, with grit size ranging from 50 to 220 mesh, though 80 is the most common. Many waterjet machines are capable of switching from pure waterjet cutting to abrasive waterjet cutting, making them uniquely versatile.

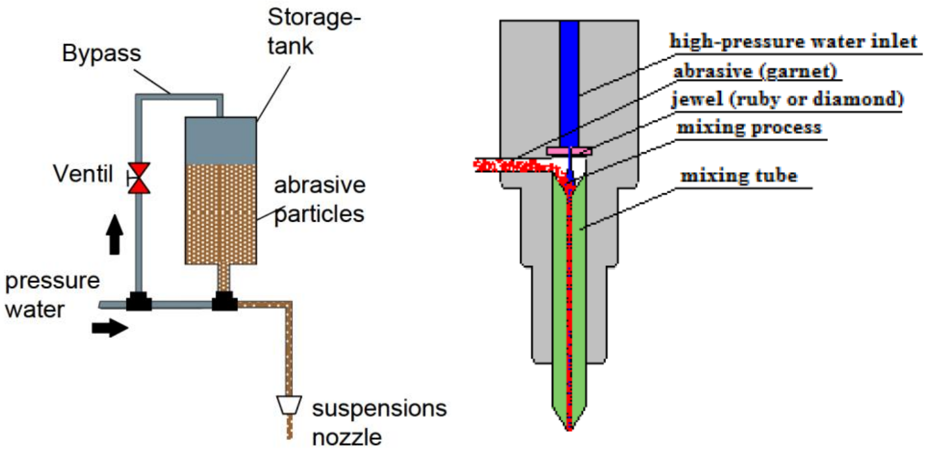

Figure 33 : Injection of abrasives

The basic mechanism of abrasive water jet cutting is extremely simple and can be summarized as follows and illustrated on the Figure 33 :

1. A very high pressure water jet is ejected from a small orifice.

2. The water jet passes through a mixing chamber thereby creating a partial vacuum.

3. Abrasive particles are drawn into the mixing chamber by the partial vacuum.

4. The abrasives are entrained into the waterjet.

5. The abrasive water jet then passes through a focusing nozzle.

6. The abrasive water jet interacts with the material and cutting take place. The cutting or controlled depth penetration of the material occurs as a result of erosion, shearing failure under rapidly changing localized stress fields or micromachining effects depending upon the specific properties of the material being profiled.

7. The movement is achieved by manipulation of the focused jet by a gantry or robot system. It is also possible to move the workpiece on a X-Y table instead of moving the jet.

8. The cutting rate is determined by process parameters such as waterjet pressure, water flow rate, abrasive mass flow, stand-off distance and the hardness of the workpiece.

The result is a stream of hydro-abrasive, which has enough power to cut through even the toughest materials. Indeed, versatility is one of the primary strengths of waterjet technology. To illustrate the sheer number of materials that can be cut using a waterjet provided a list of materials in order of cutting speed, from slowest to fastest, for any given constant material thickness :

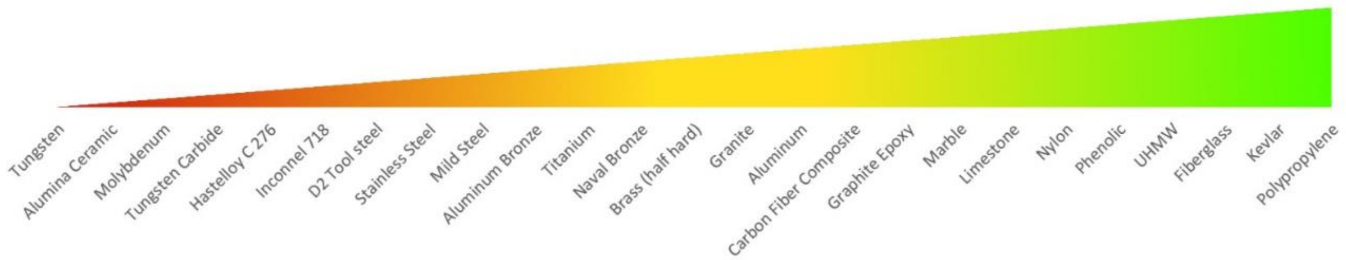

Figure 34 : Sample list of materials that can be cut on an abrasive waterjet in order of cutting speed from slowest to fastest. "An Engineer's Guide to Waterjet Cutting", Engineering.com

7.2.2 Water pressure comparison

The other main parameter of this technology is the pressure involved to cut a material. One way to understand the sheer amount of pressure involved in waterjet cutting is to compare it with other water sources in terms of maximum pressure in bars.

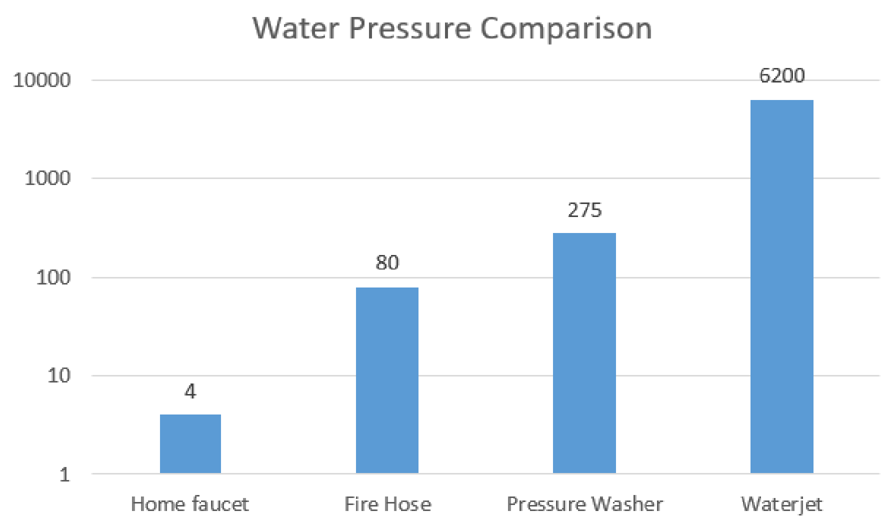

Figure 35 : Water pressure comparison (bars)

As we can see on the Figure 35, pressure can make an enormous difference. However the pressure variation within waterjet is much narrower, typically between 4000 and 6000 bars.

7.2.3 Variant of technologies

There are two basic types of pumps in waterjet: direct drive and intensifier. Direct drive pumps use a crankshaft to move the plungers that pressurize the water, whereas intensifiers use hydraulic rams. Each type has advantages and disadvantages.

Direct drive pumps are inherently a simpler design, but do require a dramatically higher amount of maintenance than an intensifier pump. Because they're a simpler designer, they're less expensive for an initial investment, but in the long run, the intensifier pumps have a dramatically lower cost of ownership.

Hence, if the initial investment is your primary concern, then a direct drive pump is the way to go. On the other hand, if you're looking for the lowest maintenance cost, an intensifier pump is the better option. This illustrates one of the basic tenets of manufacturing: it all comes down to your particular application.

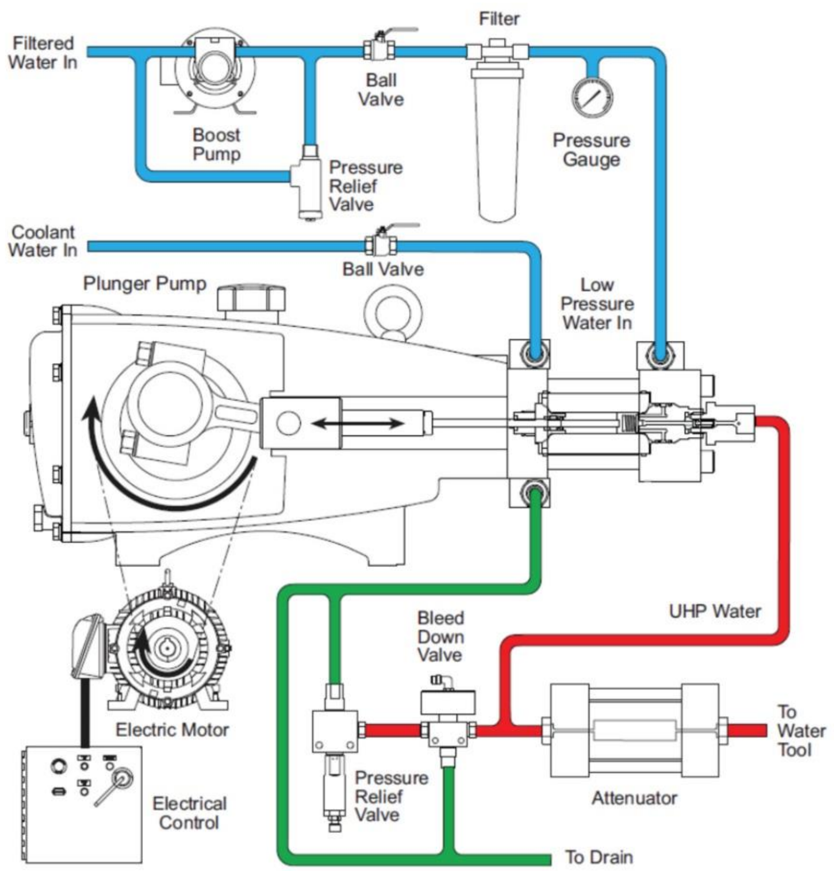

Figure 36 : Direct drive pump

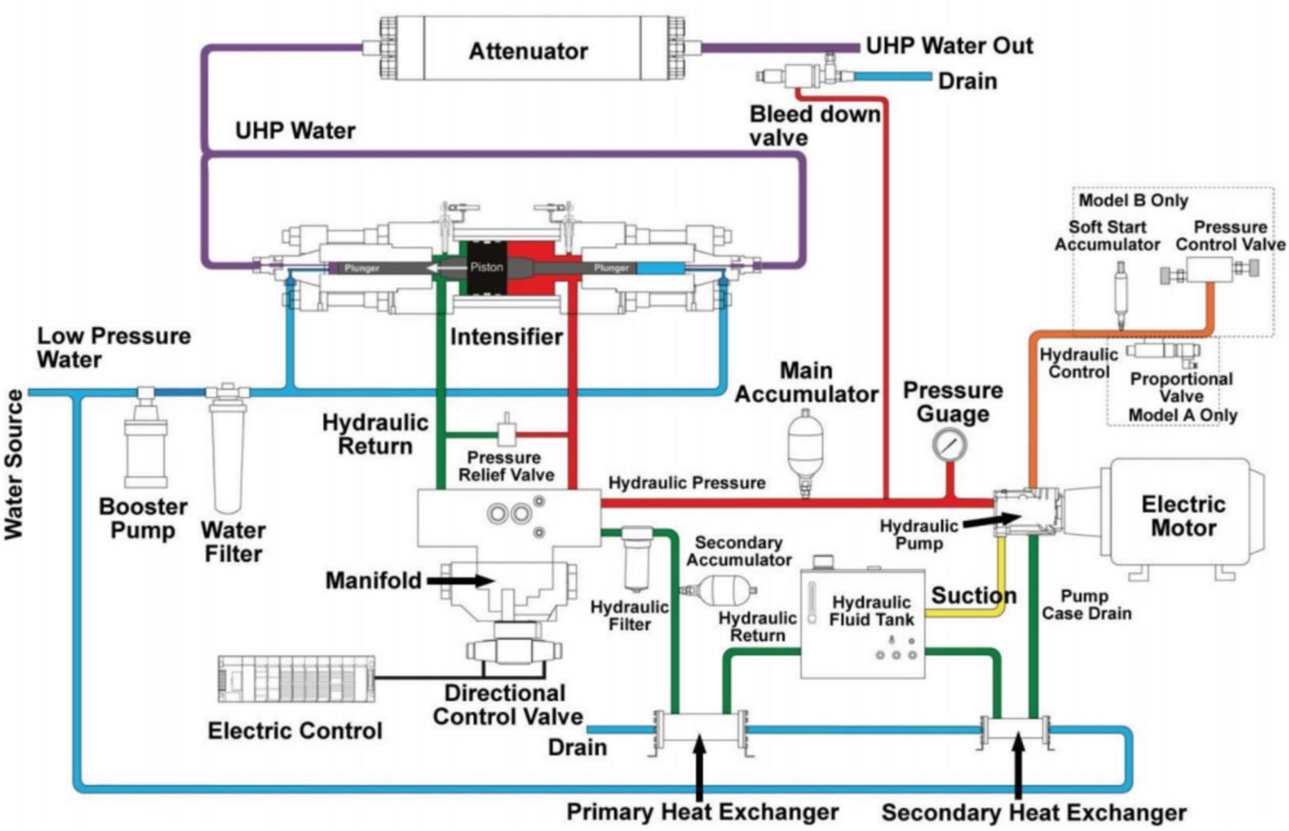

Figure 37 : Intensifier drive pump

The AWSJ cutting data are valid for a water depth of 5 m, 140 MPa pressure and +15°C cutting angle between nozzle and work piece. Other parameters like grain size, abrasive flow and water flow have also been set to the optimum for each purpose. Meanwhile systems with up to 250 MPa are available for dismantling purposes. Due to the increased hydraulic power the feed rate increases accordingly.

The quantitative comparison of AWSJ with mechanical cutting and plasma is made in section 4.2.

7.3. Mechanical saw: a technical approach

A sawing machine is a machine tool designed to cut off bar stock, tubing, pipe, or any metal stock within its capacity, or to cut sheet stock to desired contours. The sawing machine functions by bringing a saw blade containing cutting teeth in contact with the workpiece to be cut, and drawing the cutting teeth through the workpiece.

A typical bandsaw machine is driven by an electric motor through a belt transmission which permits adjustment of the blade speed through a range of speeds. The table may be tilted front-to-back or sideways to make mitered cuts. The metal cutting bandsaw machine does not require preformed bandsaw blades. An electric butt welder and grinding wheel are fastened to the sawing machine. The welder is used to weld a length of blade into a continuous band, and the grinding wheel is used to remove beads caused by the welding. Since the machine can weld its own blades, internal cutting is possible. When making internal cuts, the blade is inserted through a hole cut in the workpiece and is then welded into a band and mounted to the machine. After cutting the internal shape in the piece, the band is cut so that it can be removed.

Figure 38: band saw used to cut the reactor vessel in Rancho Seco

Figure 39: band saw used to cut the reactor vessel in Würgassen

According to its definition shearing is a mechanical separation without developing shapeless materials. It is differentiated between the following kinds of cuttings, which are assigned to shearing:

- Shear cutting;
- Blade cutting;
- Tearing;
- Breaking.

For the dismantling hydraulic shears were among other places used in the nuclear power plant in Würgassen (Germany).

One application of this technique in the field dismantling is the fractionalization of graphitic reactor components. Some 900 t of graphitic reactor components (moderators, reflectors and thermal columns fabricated from graphite or carbon stone) in Germany will sooner or later be subject to decommissioning and/or dismantling.

Fractionalizing graphitic components will reduce the volume to be stored, minimize disposal costs and reach a separation of activated/contaminated and non-radioactive parts. For example, the amount of MOSAIK type II containers needed for graphitic parts of the AVR reactor was estimated to a number of 2,511 and might be reduced down to some 50 %.

Under radiological load, each material is subject to change of its mechanical properties, and these changes in graphitic parts are substantial to this project. As the best known radiological effect on graphite, the Wigner-Energy, can easily be released through a relatively short heat treatment, it is not considered to be an issue of scientific interest. This to an even greater intent, as lots of information from theoretical and practical experience is available.

It is well known that mechanical treatment of any kind of graphite results in dust emission from the working place. For reasons of safety, this dust has to be collected during cutting operations applied to nuclear parts. Thus, another scientific goal was reached by the development of a matching filter technique to collect graphite dust emitted by the cutting process. It was applied during evaluation works on irradiated graphite.

Technique of choice in this case is the mechanical breaking of graphitic components by means of a straddling tool as it is widely in use by fire brigades. Two arms of the tool are inserted into a hole of the graphitic part and then, by means of an electro-hydraulic pump, opened.

With all sawing types, the tool is moved and supported by a feed motion. Differences exist in performance data, in the wear of tools and in the accumulation of secondary wastes:

-Fret saw:

- Cutting depths up to 100 mm;
- Wear of tool rises with the cutting depth super-proportionally;
- Tool works without coolants and lubricants in most applications.

-Bow saw:

- Also for thin-walled components suitable;
- High tool life circles lives by characteristic movement;
- Coolants and lubricants increase tool life circles;
- Handling of components with dimensions to 1 m cut lengths usually.

-Band saw:

- Handling of larger diameters;
- High tool service lives by few load of the individual tooth;
- Coolants and lubricants increase tool life circles;
- Small kerf widths and a low amount of secondary waste can be obtained by narrow dimensions of the tool;
- Very good results obtained in various decommissioning projects (as well for cutting in air as under water).

-Circular saw:

- Cutting depths in metals up to 200 mm;
- Cutting depths in concrete up to 550 mm;
- Coolants and lubricants recommendable;
- The use of remotely operated underwater circular sawing is currently common in decommissioning projects.

-Core saw/wire saw:

- Separation process is a mixture of sawing and grinding;
- Wire-cable with cutting elements of boric nitride or diamond;
- Coolants and lubricants are needed;
- Secondary waste is predominantly powder or slurry;
- Cutting depths in metals up to 300 mm;
- Cutting depths in concrete up to 1000 mm.

In general, one can say that sawing is a proved industrial technique which produces few secondary wastes (chips) easily collectable. It has been used successfully in different decommissioning projects worldwide. However, mechanical techniques require maintenance and replacement of large cutting tools in a restricted space in a controlled area. In addition, the cutting speed remains low compared to thermal techniques. These disadvantages impose long and tedious cutting operations.

7.4. Quantitative comparison

The presented cutting technologies Plasma Arc cutting, Abrasive Water Suspension Jet cutting and band saw cutting are well established powerful cutting technologies for the segmentation of reactor pressure vessels and their internals. The specific differences between each technology recommends it for specific use. Beside its advantages each technology has specific disadvantages and limits.

Thermal segmentation of metals refers to the general technique of cutting without making direct contact. In direct contrast to mechanical cutting, thermal cutting uses a medium other than a cutting edge to sever the metal such as a high-temperature flame (plasma arc). Some of the more important benefits of most thermal cutting technologies are that they can be:

- Performed under water or in air;
- Operated remotely; their use on highly radioactive materials reduces worker exposure;
- Used for extended durations of time and reduce overall costs (although set-up and take-down times are generally longer).

Thermal dismantling techniques bear a common feature; they make use of a heat source to melt, sublimate, combust or weaken a material to enable the separation of large structures to manageable formats. Often it is combined with a mechanical means to transport slug or molten substances.

A common disadvantage of all thermal techniques is the generation of solid or gaseous waste products including aerosols and suspensions that require potentially extensive filtering and conditioning.

Based on the today's experience, it appears that the pros and cons moving forward in reactor internals segmentation projects are as follows:

- PAC results in dose issues related to debris control and water clarity problems. However, it is the fastest cutting method.
- AWJC requires costly specialized water filtration and safeguard systems. Loss of debris control is a very high risk for this process. It provides very accurate cutting in narrow locations.
- Mechanical cutting provides benefits in terms of secondary waste volume and water clarity. Cutting speed is lower than for the other two methods.

	Plasma arc cutting	Band saw	Hydraulic cutting technologies
Field of application	in air / underwater	in air / underwater	underwater
Shape	1) Large diameter pipes and tanks, plate and pressure vessels 2) Simple shapes	1) Thick structures and wall or floor (<60cm) 2) Pipes, Metal	Complicated shapes
Materials	Electrically conductive material	All materials	All materials
Cutting speed (mm/min)	1) Fast 2) Slower underwater	Slow	Medium
Cost CAPEX	Medium	Medium	High
Required space (remote handling)	Ventilation and water treatment facilities required	Easy to apply on site with various variations	Ventilation and separate device for extra high-pressure water formation required
Secondary waste	1) Working gas (N_2, inert gas) 2) Slag / sludge radiation particles of more about 5 times compare to mechanical cutting 3) Large amounts of contaminated aerosols	No flame generation, no radioactive contamination such as smoke or gas	1) Used abrasive post-treatment required 2) Few air pollution
Radioprotection	Proportion of the works carried out remotely (or increase of the works carried out remotely) Note: Internal exposure of workers is the main risk for dismantling activities. Avoiding hands-on human activities is the most efficient way to reduce this risk.	Proportion of the works carried out remotely (or increase of the works carried out remotely) Note: Internal exposure of workers is the main risk for dismantling activities. Avoiding hands-on human activities is the most efficient way to reduce this risk.	Proportion of the works carried out remotely (or increase of the works carried out remotely) Note: Internal exposure of workers is the main risk for dismantling activities. Avoiding hands-on human activities is the most efficient way to reduce this risk.
Safety advantages	When remotely operated, limitation of radiation exposure	Limitation of airborne contamination (in air) or water contamination (under water)	No airborne contamination

Safety drawbacks	1) Need to address fire hazard and airborne contamination (in air) 2) Need to address radiation protection in the vicinity of filtering systems	N/A	N/A
Filtration	High water traitement and high degree of filtration	Limited water traitement and limited filtration	High water traitement and high degree of filtration
Full time estimation (process)	Medium	Slow	Medium
Maintenance	Less maintenance on site	Maintenance and wear part replacement in controlled (nuclear area).	Medium

Table 2 : Comparison of main dismantling techniques

8. ANALYSIS OF THE DIFFERENT REACTOR COMPONENTS

Generally, nuclear reactors reach a permanent operation termination period 30 to 40 years after the start of the operation. Even after a nuclear fuel is withdrawn, a nuclear reactor has residual radioactivity such as radioactivation products, and various regulations have been put in force to ensure safety management and disposal for decommissioning of such a nuclear reactor.

The primary challenges of a PWR RVI segmentation and packaging project are to separate the highly activated materials from the less-activated materials and to package them into appropriate containers for disposal. This process requires the specific-sequence disassembly of various internals components and systems that must be temporarily staged in the refueling cavity where they await further segmentation. Since most refueling cavities have limited space, it is important to plan carefully so that the available space is optimized.

Removal of the reactor internals and the reactor pressure vessel is usually on the critical path of the nuclear power plant decommissioning program. It is also expected to belong to the most difficult activities. Due to the severe radiological conditions of the reactor internals, these must be segmented underwater It is therefore recommended that the reactor internals are removed as early as possible in the plant dismantling sequence. It is therefore recommended that the reactor internals segmentation has to be carried out inside the reactor building.

8.1. General description of PWR and BWR reactors

The main design is the pressurized water reactor (PWR) which has water at over 300°C under pressure in its primary cooling/heat transfer circuit, and generates steam in a secondary circuit. The less numerous boiling water reactor (BWR) makes steam in the primary circuit above the reactor core, at similar temperatures and pressure. Both types use water as both coolant and moderator, to slow neutrons. Since water normally boils at 100°C, they have robust steel pressure vessels or tubes to enable the higher operating temperature.

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	301	286	enriched UO_2	water	water
Boiling water reactor (BWR)	USA, Japan, Sweden	64	65	enriched UO_2	water	water

Figure 40: Nuclear power plants in commercial operation or operable

The reactor core is positioned and supported by the lower internals and upper internals assembly. The individual fuel assemblies are positioned by fuel pins in the lower and upper core plates. These pins control the orientation of the core with respect to the lower internals and upper internals. The lower internals are aligned with the upper internals by the upper core plate alignment pins and secondarily by the head/vessel alignment pins. The lower internals are orientated to the vessel by the lower radial keys and by the head/vessel alignment pins.

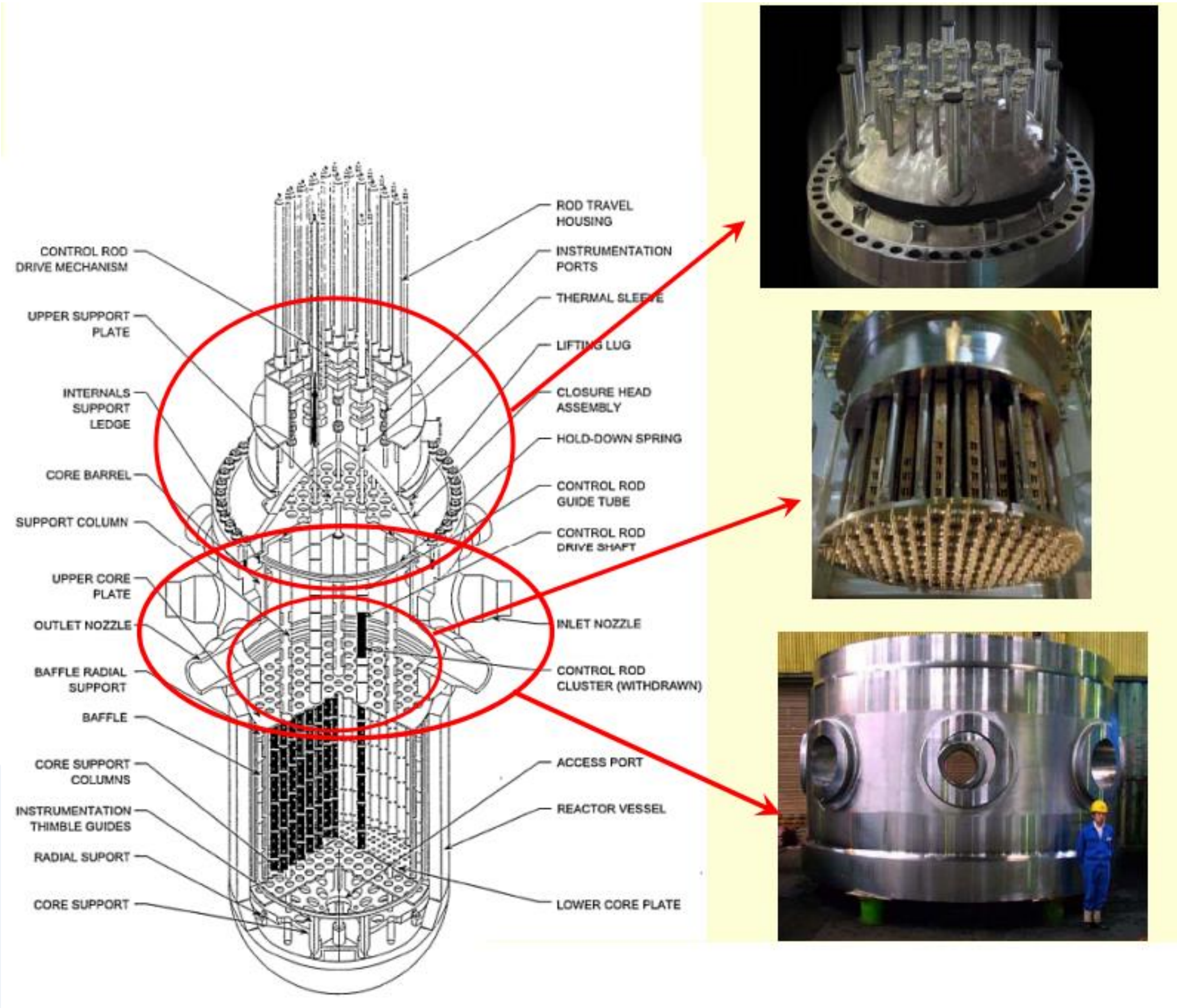

Figure 41: Internals of PWR

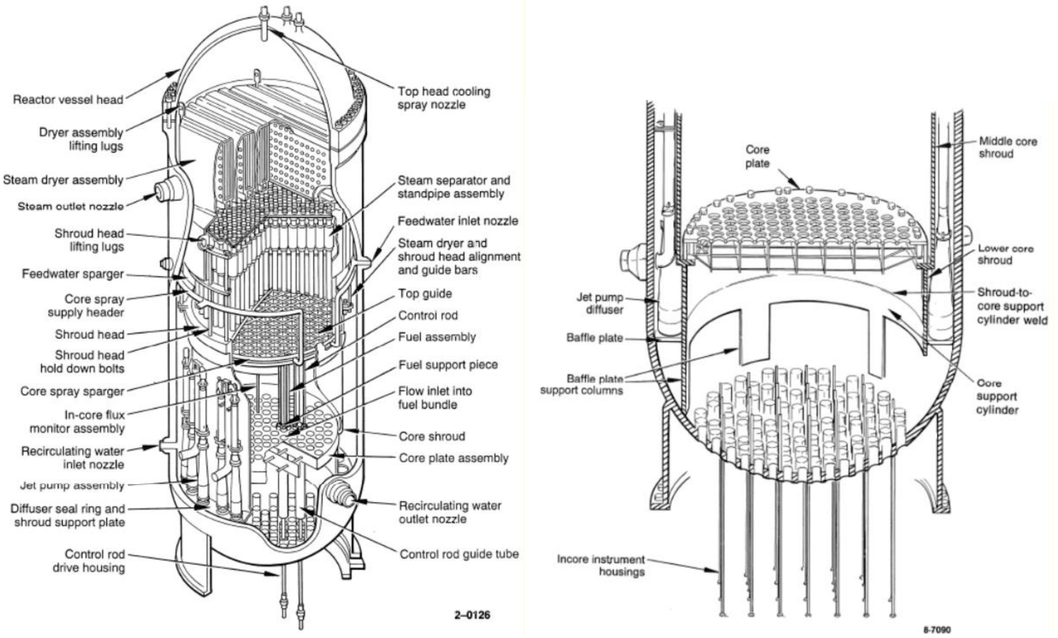

Figure 42: Internals of BWR

The reactor vessel internals are complex metal assemblies that are installed inside the reactor pressure vessel to hold fuel, direct flow, route instrumentation, and provide physical controls for controlling reactivity. RVI geometries vary considerably depending on the type, size, and design of the reactor. This report includes a high-level description of the internals of the two most common light water reactor designs, Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR).

The major RVI components are generally made from stainless steel subcomponents assembled with bolted and welded connections. Typically, the assembly rests on a mating flange at the top of the cylindrical Reactor Pressure Vessel (RPV) where the semi-spherical head is bolted on. On the other hand, the lower internals are permanently welded at their. The removable parts of the RIV have lifting points in order to move the reactor head during a shutdown for refueling or during an inspection.

Both Pressurized water reactor (PWR) and Boiling water reactor (BWR) does have a number of identical, similar and different characteristics as well for operation and for construction.

<u>Construction similarities:</u>

- Both the PWR and BWR types have an external (pressure) vessel and an internal barrel in which all process actuators are positioned.
- Both types carry a bolted removable cap on top of their external vessels.
- Both types have removable fuel and control elements.

<u>Construction differences:</u>

- In general, a PWR generates high pressurized water to feed a number of surrounding steam generators, while a BWR generates high pressurized steam.

- In a typical PW type reactor, fuel assemblies are positioned in a core holder on top of the internal barrel and directly below water level in which core holder the reaction is controlled by inserting absorbent rods in between the series of fuel rods.
- Fuel assemblies in a BW type reactor are moved upwards from below a set of poisoning plates to throttle the reaction and must descent to regain reaction.

8.2. PWR and BWR Internals

Both PWR and BWR external vessels are lathed/milled parts welded together into a pipe shaped body covered with a solid, single body lathed/milled cap. The cap is bolted onto the main vessel and therefor can be removed

- **PWR internals (RVI) comprises two major compartments:** the upper internals and lower internals. The upper internals (plenum) comprises a tube grid (Core Holder) bolted into the external vessel and a series of fuel bars, individually bolted on top of the core holder top grid and the core holder itself. All these can be removed separately.
- **The lower PWR internals** are bolted into the external vessel and can be removed also (core support) carries the movable fuel compartments.
- **Component Properties concerning sectioning** (regardless of contamination) involve material type (Mat.), thickness and section area (chipped volume), gap width which translates into accessibility, total volume i.e. mass of the component.

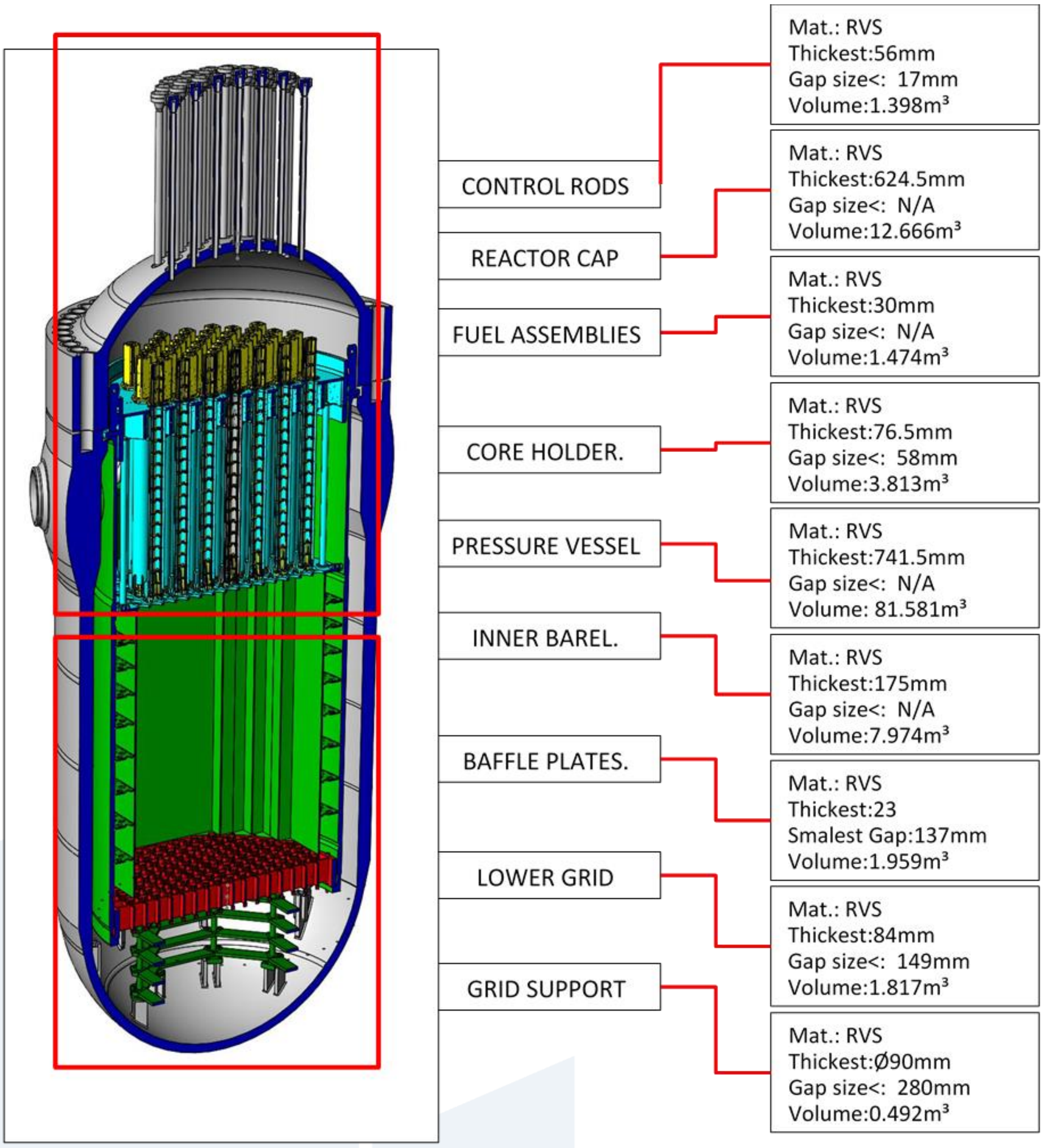

Figure 43 : PWR internals description

- **BWR internals** also contains an upper and a lower compartment, whereas the upper compartment comprises the steam separator and the steam dryer while the lower internals comprises the control rods the poisoning blades and instrumentation. Steam separator, steam dryer, fuel bars, poisoning blades and upper grid all can be removed.

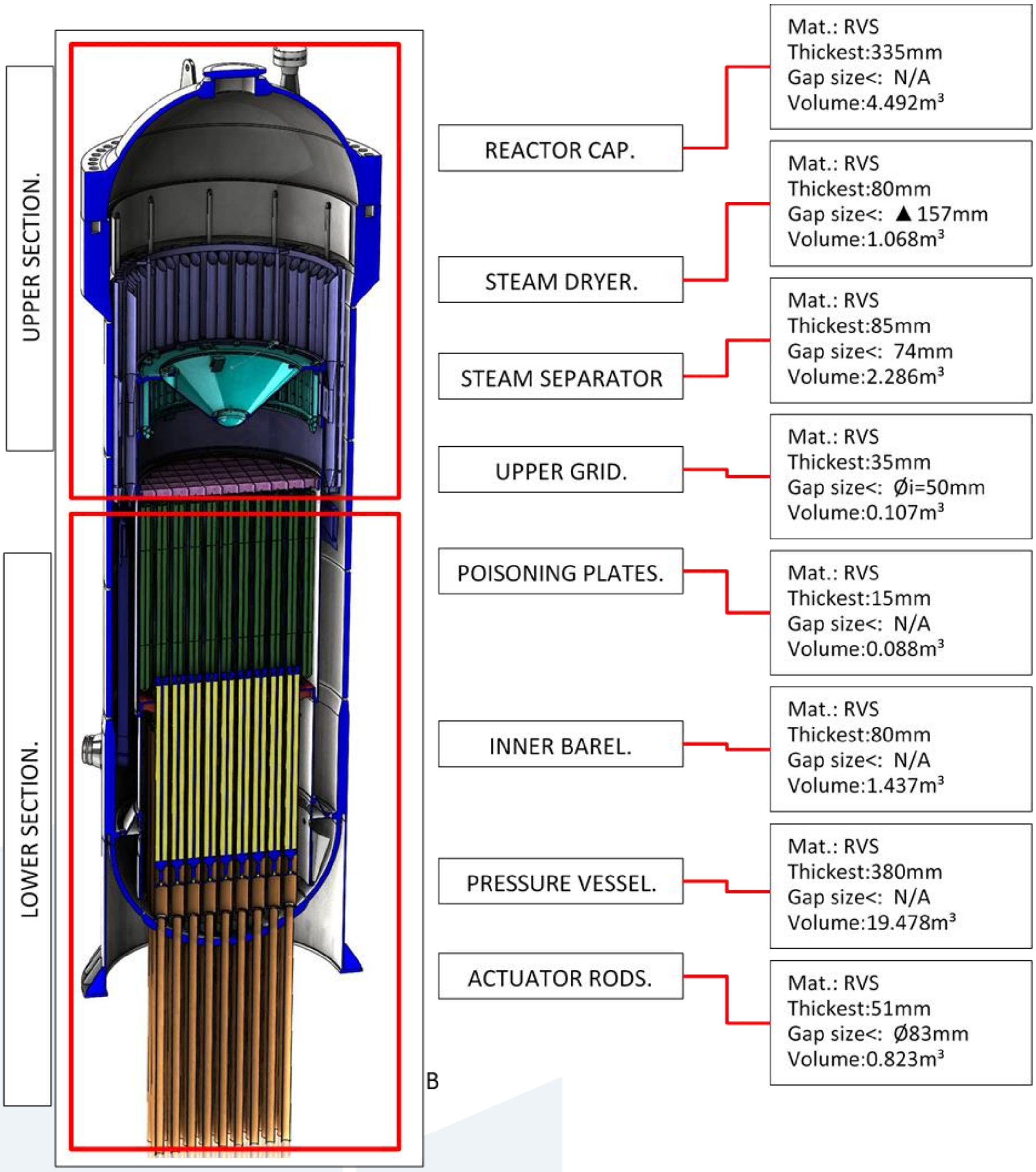

Figure 44: BWR internals description

Small (Light) components typically removed for sectioning, away from the main vessel are:

- Rector Cap
- fuel assemblies.
- Poisoning Plates
- Lower support frame.

Large (Heavy) Component typically to be left in or near the water basin are the:

- Steam Separator Cap

- Steam Separator and Dryer,
- Core Holder,
- Upper and lower grid,
- Reaction Section
- External (Pressure) Vessel.

Components details :

- **Solid featured components:** Sawing solid bodies or solid walls up to 300mm shouldn't cause any problems using regular tools such as bow saw, reciprocating saw, chain saw, or any other type of saw even large diameter blade saw.
- **Thick wall featured components:** Pipe, beam or tube-shaped components with wall thickness over 300mm mainly are very large objects and might first be sectioned into smaller parts by using chain, cable or rope saw. In some case special designed bow saw tools can be advisable. Smaller parts then can be handled separately when still too large for packaging.
- **Pipe featured components:** In most cases pipes are assembled very tight to each other which leave very narrow spaces in between. An obvious approach on this issue is starting on the outer edge of the pipe assembly to work its way in.
- **Tube featured components:** These often can be sawed diametrically, inside the tubes with a blade saw and longitudinal with a scissor or a chip cutter. In case of using or waterjet tools, cutting can apply in any direction and askew or even toroidal cuts can be accomplished.
- **Plate featured components:** Commonly used tools for sheet metal sectioning are scissors and chip cutter. Although bow sawing can be used, this often will be compromised by vibration and deforming issues.
- **Mixed features:** Though each type of feature can be considered in its particular way, most components are a mixture of some few. A in deep study of each feature within the particular component will help to determine the right series of tools if not reduce it to a single one.

8.3. Radiological aspects

One of the most challenging tasks during plant decommissioning is considered as the removal of highly radioactive internal components of the reactor pressure vessel. It is also expected to belong to the most difficult activities, because these must be cut underwater due to the severe radiological conditions of the RPV internals.

The radiological effect must be assessed for the decommissioning of its NPP after permanently shut down, because it is different values among the commercial NPPs due to the different operating conditions and material conditions. To design the decommissioning scenario under the ALARA principle and calculate exposure dose rate for worker, the assessment of the external radiation level is important in the NPP. And also to perform the waste classification and packaging, the detail radiological information can be obtained from results of the radioactivity inventory assessment. Since the core baffle assembly closes proximately to the active region of the fuel during operation, it is the most highly activated component of the RPV internals. Impurities such as cobalt and other metal such as nickel in the stainless steel are ultimately activated and contribute to the high curie inventories in reactor and reactor internals.

Since the activity of a reactor depends mainly on the fuel used and the operating time of the reactor, it is difficult to estimate the contamination present inside the core. As an example, the following figure shows the average neutron flux in an operating reactor and gives an idea of the most contaminated parts inside a conventional nuclear reactor. It has been clearly demonstrated that the neutron flux decreases as the distance from the fuel assembly increases. We note that the neutron flux is higher in the lower part of the reactor and will therefore cause greater contamination of the components located there. it has also been discovered that the neutron flux affects the activation of the materials and waste classification. The high concentrations of 55Fe, 63Ni, and 60Co have also been observed in the RV, which mainly consists of carbon steel. Similarly, high concentrations of 63Ni, 55Fe, and 60Co have also been observed in the RVI, which mainly consists of stainless steel.

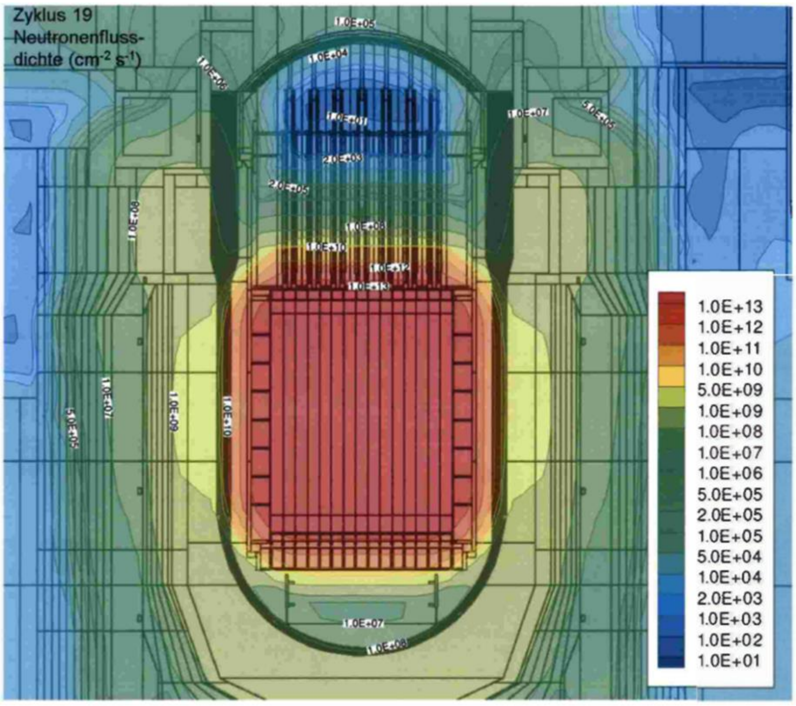

Figure 45: Neutron flux inside the primary vessel

An example for the dismantling of a Korean reactor is shown in the following picture and presents the radiological Assessment Results 10 Years after Shutdown of Kori Unit 1. These data are only illustrative and do not present a generic case for the dismantling of a European PWR.

Component name	Weight (kg)	Volume (m^3)	Total specific activity (Bq/g)	Co-60 specific activity (Bq/g)	Ni-63 specific activity (Bq/g)
Vessel Internal					
Baffle plate	9,523	76.40	3.24E+09	2.18E+09	5.56E+08
Barrel	30,472	244.48	1.70E+09	9.57E+08	2.92E+08
Baffle former	2,612	20.96	2.24E+08	1.59E+08	3.48E+07
Thermal shield	23,697	190.13	3.13E+08	2.21E+08	4.85E+07
Upper support assembly	6,153	49.37	5.79E+01	1.17E-01	2.92E+01
Upper core plate	1,534	12.31	3.72E+06	7.51E+03	1.88E+06
Guide tube	8,419	67.55	3.14E+03	6.27E+00	1.61E+03
Upper support column	20,713	166.18	3.80E+03	7.58E+00	1.95E+03
Lower core plate	1,682	13.50	7.02E+05	1.42E+03	3.54E+05
Core support plate	4,192	33.63	2.99E+03	5.97E+00	1.54E+03
Reactor vessel (without reactor head)	185,397	1,465.00	9.07E+06	5.80E+06	1.81E+05

Figure 46 : Estimation of contamination of a Korean Reactor (Kori 1)

8.4. Preparation before segmentation

It is necessary to define the sequential steps required to segment, separate, and package each individual component of RPV in the segmentation and packaging plan, based on an radiological assessment. Therefore, the dismantling strategy is established in the most cost effective manner, in consideration of many factors such as waste container selection, disposal costs or transportation requirements. However the processing of all this information is beyond the scope of this note and will be discussed in more detail in future developments. In this section, a proposal for a reactor dismantling plan is presented below, taking into account the following criteria:

1) Activation analysis of the reactor vessel and internals to define waste characterization and classification of the reactor components.
2) Evaluation of disposal options depending on waste characterization and the waste acceptance criteria.
3) Conceptual tooling development based on waste characterization and disposal option, which are developed using collected data and information
4) Segmentation and packaging plan contains optimization packaging efficiency while considering segmentation schedule. And the plan defines type and quantity of waste containers and defines location and number of cuts per waste container

Based on the dismantling experience of the RPV internals, developing process of the segmentation and packaging plan is usually made at first by consideration of waste acceptance criteria, available type and size of containers for the disposal options.

For making the segmentation work easier and safer, the preparation activity has to be performed including some plant system and civil structure modifications. To define the scope of the preparation activity, required space requirements at first are defined according to the applied cutting technology, associated remote handling equipment such as manipulator and waste handling tools and container. And then the environmental conditions of the reactor building especially around of the reactor cavity are carefully reviewed in view of the required space requirements for the cutting activity. Depending on its environmental conditions, it will be determined a number of preparation activity, which have to be performed before the actual cutting activities can start.

The levels and dimensions of the cut positions are based on the expected activity levels and the dimensions of the waste containers. For example the preparation activities will include cutting of some wall around the reactor cavity, securing the pool integrity, characterizing the internals, retrieval of existing components, installing a new working bridge and cleaning of the pool floor and water.

The sealing of the pool walls was a challenging task as the initial leakage was substantial and coming from all over the pool area. The floor of the reactor pool was therefore reinforced with a 15 cm thick concrete layer whereas leakages in the wall were sealed by injecting sealant into all identified cavities and the whole surface was then painted with an impermeable paint. The leakages in the spent fuel pool steel liner had to be sealed under water because highly irradiated operational waste was stored in that pool which prevented draining of it. This operation was performed using divers.

In Chooz A, the entrance to the reactor cave has been enlarged to allow access to some heavy equipment, like the future reactor vessel stand that will be sealing the reactor pit after removal of the vessel. Other significant civil work modifications occurred for allowing the installation of a hot cell for the future drying and characterization of the cut internals and final container loading. To achieve that, a previous steam generator pit has been sealed with a concrete slab to create the necessary space for installing the hot cell. Another steam generator pit has been also sealed for installing the future dry cutting workshop. Other significant works had to be performed for bringing new electrical cabinets and installing new ventilation ducts.

At José Cabrera, before installing the new working bridge, the spent fuel racks had to be removed from the spent fuel pool. However, some operational waste was still stored in rack cells and needed to be segmented and packages first. A number of operational waste such as RCCA's, primary sources, secondary sources were cut with shearing tools and positioned into special designed canisters that was later put into the Multi-Purpose Canisters along with the other high activated waste.

At Chooz A, the operational waste was stored in the vessel in the previous core region. It included dummy fuel, Zircaloy control rod followers, neutron source rods, MOX bottom pieces, control rods, adaptors. The figure below shows the Chooz A operational waste inventory stored in the reactor vessel.

Figure 47: Waste inventory in Chooz A

Cutting of the wall may be necessary to provide access to a deeper pool and led to better water shielding for the operators. That constituted a substantial design change and detailed structural analyses had to be performed to demonstrate that this demolition is safe. The sealing of the pool walls was a challenging task as the initial leakage was substantial and coming from all over the pool area. A new working bridge crane may have to be installed in the cavity with higher capacity, and placed at a height compatible with the maximum water level. This new arrangement has the additional benefit of placing the access to the bridge at the floor level, simplifying the access of personal and equipment to it.

8.5. Reactor Internals removal sequence

The first step of the segmentation is to remove the removable parts of the reactor. These parts are regularly removed when the reactor is shut down for refueling. All items will be removed using normal operational methods and, generally, disposed of without segmentation if their size allows.

For this description in general deals with the internal components, it initially assumes the outer vessel to be emptied from any fluid and has the cap removed and all surrounding tools and equipment is in place. Dependent on the type of reactor sequence of disassembling will also differ.

- **PWR** has two major RVI components: upper internals and lower internals. The upper internals (plenum) has to be removed for individual separation, and the lower internals (core support) has besides its fixed components the movable fuel packages which also are to be removed for individual sectioning.
- **BWR** has three major internals components: the steam separator, the steam dryer, and the lower internals. The steam separator and dryer and all fuel bars and all compartments and poisoning plates as well are removed for sectioning.
  1.

Sequence :

- The core holder is lifted out of the inner barrel, brought in position on a rotation table.
- Guide pipes are cut to release the top grid.
- The top grid is placed back into the outer barrel.
- The remainder of the guide pipes is cut into pieces.
- The remaining raster is divided into rectangular parts.
- The upper raster plate is lifted out again and cut likewise into rectangular pieces.
- The outer barrel and the baffle plates within is lifted onto the rotation table and cut into rectangular segments.
- The remaining lower grid is cut into rectangular parts.
- The lower grid support is cut into manageable pieces.
- The above points describe only the PWR procedure. A similar BWR procedure is applicable.

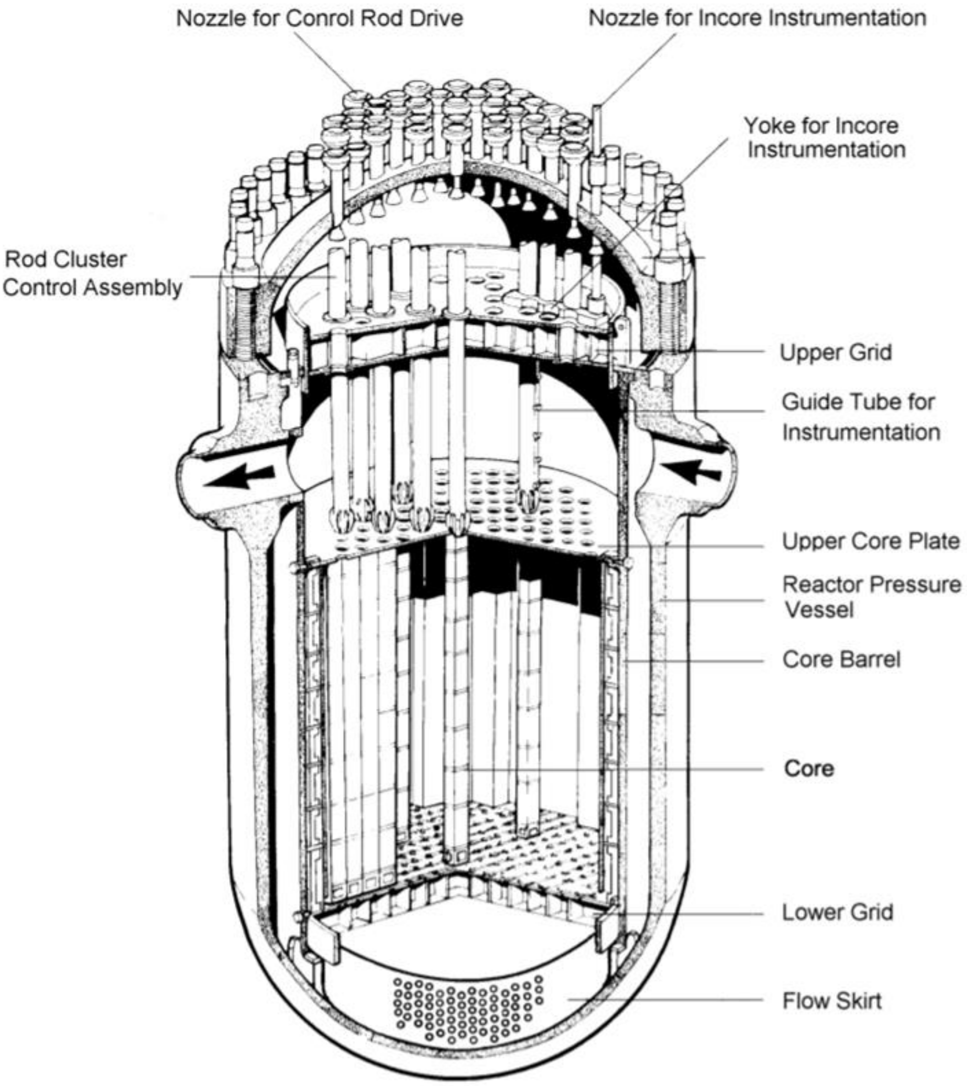

Figure 48: Segmentation of reactor internals

8.6. Reactor Pressure Vessel

Generally, an RPV is composed of a reactor vessel (RV) that has a comparatively simple structure but very large thickness and RV internals (RVI) that have very complex structures but comparatively thin walls. Reactor Pressure Vessels are thick steel containers that hold nuclear fuel when the reactors operate.

The vessels provide one of several barriers that keep radioactive fuel contained and out of the environment. During the reactor operation, it generates subatomic particles called neutrons. Some of these neutrons hit atoms in the steel as they leave the core and when these are captured by the steel they can make the steel radioactive.

The thickness of the RPV is generally greater than 150 mm and greater than 300 mm in some areas. The main parameter in the cutting process of a RPV is the capacity of a tool to cut large thickness of steel. .

Indeed, once the reactor internals have been removed and packaged in containers, the sequential cutting of the reactor vessel can begin and the simplicity of the shape of the empty vessel does not impose any increased positioning difficulties compared to the cutting of the internals. As soon as the choice of packaging is made, it is possible to define a cutting sequence of the reactor vessel into pieces of more or less important size.

Cases studies:

Rancho Seco and Würgassen were chosen as decommissioning projects in which RPVs were segmented by remote dismantling equipment. Rancho Seco completed segmentation of the RPV using the HPAWJ and a diamond wire saw between 2006 and 2007. Würgassen completed segmentation of the RPV using the HPAWJ and the band saw between 2008 and 2010.

The reactor of Rancho Seco is a PWR reactor and was operated commercially from 1975 to 1989. The decommissioning project began in early 1997 and ended in October 2009.

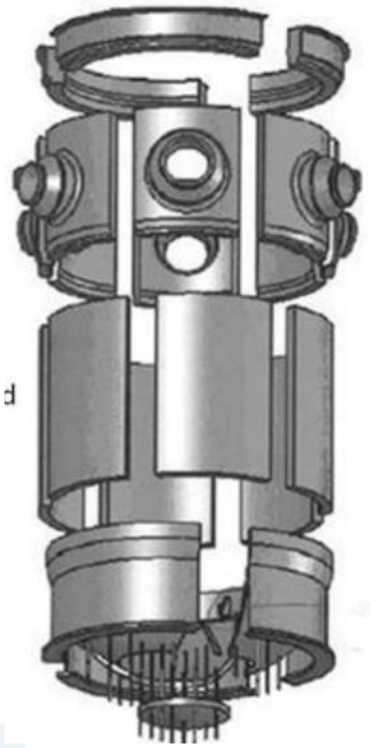

Figure 49: Rancho Seco segmentation

The RV was segmented into 21 pieces. The precise operation of the HPAWJ ensured that actual cuts were very close to the specifications in terms of the projected overall size and weight. The cutting tools used in Rancho Seco were the HPAWJ for the RV and the diamond wire saw for the reactor head.

The reactor at Würgassen was a 640MWt boiling water reactor and was shut down in September 1995. The decommissioning project began in 2003 and ended in 2008. The cutting tools used in Würgassen were the HPAWJ for the reactor cylinder slice, the reactor head, and the reactor bottom, and the band saw to segment the slices of the reactor cylinder. The band saw was used to segment slices of the cylinder into several pieces. Total cut segments were 252 pieces.

Evaluation results are examined to conclude that the dismantling operation at Würgassen was much more efficient than that at Rancho Seco. In terms of cutting tools, the HPAWJ and the mechanical saw are excellent and have complementary characteristics to each other at the same time. A combination of the two cutting tools can produce a synergy effect.

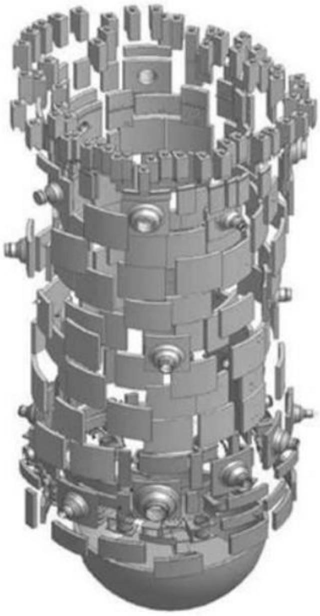

Figure 50 : Würgassen segmentation

9. CONCLUSION

In NPP decommissioning operations, the dismantling of NPP reactor vessels and their internals have proved in the recent years to belong to the most challenging industrial operations.

This report has presented different decommissioning techniques commonly used to achieve these operations, based upon real-life decommissioning feedback on reactors worldwide.

From an operational point of view, three main techniques are commonly used (PAC, Band saw, AWJC), with their own advantages (reliability and general performance, efficiency, limitation of waste generation…) and drawbacks (costs, safety issues, environmental impact…).

It appears that these techniques are not absolutely satisfactory regarding several of these aspects, one them being the maximal thickness required for the vessels segmentation (up to 300 mm).

So, the development of a new cutting technique, or the improvement of existing technique, seems to be desirable to address the decommissioning of the most challenging equipment issue.

It is important to well prepare the dismantling of a reactor vessel and its internals in advance. Such a project is not limited to the pure segmentation activities. A detailed study of the optimum dismantling scenario must be done upfront, considering the available plant systems and infrastructure. Especially for old plants, significant plant modifications need sometimes to be considered for completing the reactor dismantling, including civil work modifications, new water filtration system, new power supply or new HVAC system.