Cutting Reactor Pressure Vessels and their Internals

– Trends on Selected Technologies – 10247

Robert W. Henderson, Ludger Eickelpasch
NUKEM Technologies GmbH
Industriestrasse 13, 63755 Alzenau, Germany
info@nukemtechnologies.de

ABSTRACT

Many Nuclear Power Plants have been dismantled during the last 2 decades. An essential part of this work is the dismantling of the Reactor Pressure Vessel and its Internals. For this purpose a wide variety of different cutting technologies have been developed, adapted and applied.
A detailed introduction to Plasma Arc cutting, Contact Arc Metal cutting and Abrasive Water Suspension Jet cutting is given, as it turned out that these cutting technologies are particularly suitable for these typ of segmentation work. A comparison of these technologies including gaseous emissions, cutting power, manipulator requirements as well as selected design approaches are given from specific examples. Process limits as well as actual limits of application are presented.

INTRODUCTION

Dismantling the **R**eactor **P**ressure **V**essel (RPV) and the **R**eactor Pressure **V**essel **I**nternals (RVI) of a nuclear power plant (NPP) is a challenging task.
Very high dose rates (>10 Sv/h) and a wide range of nuclides with relevant consequences for radiation protection and waste characterisation have to be considered, as well as "design parameters". The design of a RPV typically results in high wall thicknesses, complex geometric structures and materials with high mechanical and thermal load capacities.
Due to the combination of high radioactive inventory, complex design and "strong" materials specific requirements on the cutting technology are needed.

From a wide variety of field-tested cutting technologies the following techniques turned out to be specifically powerful and flexible:

- Plasma Arc cutting
- Contact Arc Metal cutting
- Abrasive Water Suspension Jet cutting

PLASMA ARC CUTTING

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.

Plasma gas streams out with high velocity through the plasma torch nozzle. Between the cathode inside of the plasma torch and the plasma nozzle an electric arc will be ignited and the electric energy will be absorbed by the gas. The energy dissociates and ionises the streaming plasma gas. Therefore the plasma

gas itself will be electrically conductive. This small plasma arc is called pilot plasma arc and has relatively low energy.
If the pilot plasma arc touches the material to be cut, the control unit from the plasma source switches off the electric circuit immediately so the current circuit runs between cathode and material. In parallel the strength of the current will be increased.
This ionised plasma gas is physically instable and will recombine immediately. Therefore the former dissociated and ionised energy will be set free as heat up to 30000 K and melting a kerf into each electric conductive material.

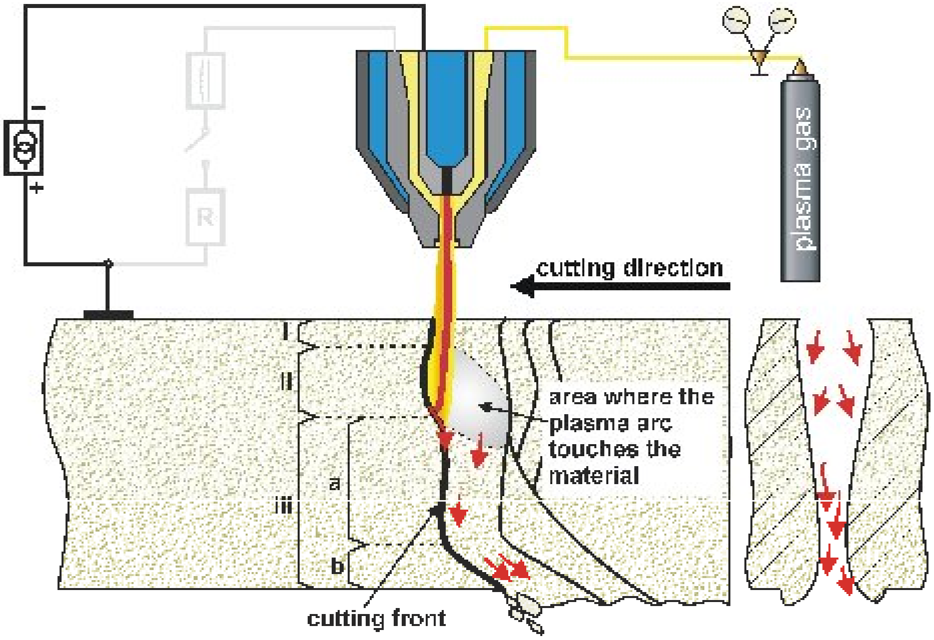

Fig. 1: Principle of Under Water Plasma Arc cutting

Following parameters have influences on the cutting power: The electric power of the plasma source, the type of plasma gas and the design of plasma torch and plasma nozzle.
State of the art is underwater Plasma Arc cutting. A special underwater torch creates a small dry cutting space. In this zone the plasma arc can be burn (Fig. 1).

To generate an electric arc and its surrounding plasma arc the material to be cut must be electrically conductive. Therefore all electric materials (metals) can be cut. The maximum material thickness which can be cut depends on various factors, thereof two are described below.

The enthalpy of the plasma gases should be high. Generally the plasma gas is a combination of argon (low enthalpy), necessary for starting the plasma process, and one or two additional plasma gases. For very thick material hydrogen or hydrogen-nitrogen combination is recommended. For middle thickness materials nitrogen can be used and for thin materials normal air can be used.

Fig. 2: Plasma power sources with control board, cooling unit and supply lines

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 Ampere (250 Volt). 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 Ampere (280 Volt) for underwater cutting tasks (Fig. 2). 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 [1].

One limit of use is the structure of the component which will be cut. Big gaps between two elements cannot be bridged with standard equipment.
For control of a successful cut through the material the normal observation cameras can not be used because the intensity of plasma light is too high for normal cameras. Special absorption filters, which will move in front of the cameras, can be used. Alternatively a special current/voltage measurement unit can observe the cutting process. A non-optimum cut can be detected by these parameters during the cutting process.

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 [2]. 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.

CONTACT ARC METAL CUTTING (CAMC)

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 [3]. The structure of the components which will be cut is not relevant. Gaps and hollow structures are not a problem. In contrast to the two other described cutting technologies, CAMC is primarily designed for dismantling tasks and can be used under water only.

The principle structure of a CAMC cutting unit is shown in Fig. 3. A carbon fibre electrode will be moved with a manipulator or guiding system slowly against the material which has to be cut. The electrode is surrounded by a strong water jet curtain. In a cyclic process of resistance heat by contact and free burning high current arc the material will be melting off in the contact zone between electrode and material. Graphite's material property – no liquid phase exists – prevents the welding between carbon fibre electrode and material which will be cut. The strong water jet curtain which surrounds the electrode pushes the molten material out of the developing kerf. During this melting process, the carbon fibre electrode will be used up and must be replaced from time to time.

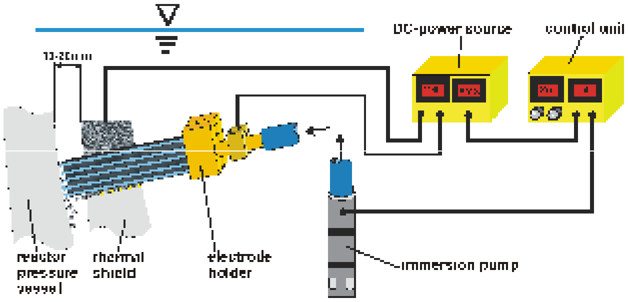

Fig. 3: Working principle of CAMC

Based on the solid cutting electrode, the dimensions of the cutting tool itself is bigger in comparison with the other technologies. The precise dimensions depend mainly on the dimensions of the electrode, which will be customised for the components to be cut. In principle the shape of the cutting electrode is like a blade of a knife. According to this blade design CAMC can cut only in straight lines. This constrains the field of applications.

The central part of the CAMC unit is a thyristor-controlled DC-power source. The preferred applied source type works with maximum 700 Ampere /58 Volts. This source will be controlled from the control board.
The electrode holder (tool) is designed for simple adaptation to a manipulator or guiding machine. A variable clamp mechanism enables the fast change of consumed carbon fibre electrodes. The exchange of a consumed electrode through a new electrode can be handled in approx. 60 seconds by one person. The shape of the electrodes itself is variable and should be optimised on the cutting task.

The water jet curtain surrounding the electrode is very important for the cutting results. The water jet curtain itself will be created by special nozzles which are part of the electrode holder. A high pressure immersion pump produces the required water pressure which is carried via a hose to the cutting holder. In order to avoid water addition by the CAMC process shielding water from the surrounding pool should be used to feed the immersion pump.
During the cutting process particles will be produced. The dimensions of the particles are similar to the particles generated during Plasma Arc cutting. Due to the fact that the cutting kerf is wider, the sum of particles is higher. That means the water cleaning equipment must be more powerful or after a successful cut a break is necessary for cleaning the water before the next cut can be prepared. During the cutting process it is not necessary to observe the cutting process via cameras.

In principle CAMC can be used for all underwater dismantling tasks. But the preferred field of application is cutting of complicated structures (hollows, kerfs) or materials which are not to be cut by conventional technologies. The second field of application is to cut components with high material thickness. In 2009 NUKEM Technologies in cooperation with the Institute of Material Science Hannover, Germany, investigated the use of CAMC for material thicknesses in the range of a reactor pressure vessel flange. A mock up of 550 mm thickness was successfully cut. The set up for the investigation is shown in Fig 4.

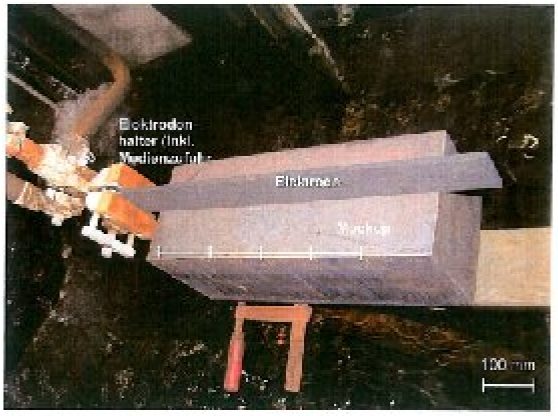

Fig. 4: Mock up for cutting thick materials with CAMC

In nuclear dismantling practice the CAMC-cutting technology was used as an intervention tool in nuclear power plant Greifswald/Germany and for the dismantling of a part of the thermal shield from the multi-purpose research reactor (MZFR) in Karlsruhe/Germany.

ABRASIVE WATER SUSPENSION JET CUTTING

Abrasive Water Suspension Jet cutting (AWSJ) is a micro grinding process. A high pressure water jet accelerates abrasive particles and carries these particles to the material which has to be cut. The abrasive particles grind small chippings from the material and therefore produce a kerf.

A pressure generator increases the water pressure up to 250 MPa. Through the main high-pressure pipeline the water flows to the suspension nozzle. A bypass-pipeline deflects a part of the water into an abrasive storage vessel. In the abrasive storage vessel slurry of abrasive particles and water are stored. The bypass water carries the slurry to the mixing valve which will join the slurry and the high pressure water to a suspension. This suspension is transported via a pipeline and a flexible high pressure hose to the cutting tool (nozzle). The nozzle accelerates the suspension again before it meets the material which will be cut. The working principle of AWSJ is shown in Fig 5.

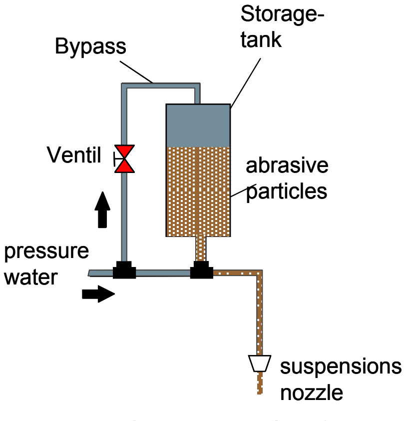

Fig.5: Working principle of AWSJ

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 AWSJ-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.

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.

The limits of maximum material thickness which can be cut depend mainly on the pressure generator and valve technology. Actually approx. 300 mm steel can be cut using a pressure generator for 250 MPa.

For producing the high water pressure a pressure generator is necessary. For AWSJ mostly plunger pumps are used.

TECHNOLOGY COMPARISON

All three cutting technologies have specific advantages and disadvantages; one aspect is the emission of gases.

By using thermal cutting processes under water gaseous emissions occur. These emissions ascend to the water surface and have to be exhausted. Beside inert gases and air typically the following gases can occur during the process:

- Nitrogen Oxides
- Carbon Oxides
- Hydrogen

The gases are of two different origins:

1) Process Gases
2) Generated Gases

Plasma Arc Cutting

For Plasma Arc cutting of stainless steel parts under water usually a process gas mixture of Argon and Hydrogen or Nitrogen is used. As described above the process gases are dissociated and ionized in the electric arc and recombine immediately inside the kerf. The resulting gaseous emissions are a very low amount of nitrogen oxides and carbon monoxide and negligible. Additionally the surrounding medium, in this case the water, is dissociated by the high energy density inside the plasma arc, resulting in the generation of hydrogen. A typical emission rate is around 12 dm^3/min for cutting 80 mm thick stainless steel plates [2].

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 [4]. An interlock between exhaust air system and cutting process is recommended due to control and safety reasons.

CAMC

No process gases are used for the contact arc metal cutting process. The generated gases are the result of the heat from the electric arc and the water electrolysis at the electrodes surfaces due to the DC voltage. The cutting electrodes are made of carbon and wear during the process. Carbon monoxide is generated with a typical emission rate of 31,2 dm^3/min for cutting stainless steel plates with a thickness of 80 mm. The DC voltage is applied to the electrode and the metallic part that has to be cut. At all surfaces of these parts, that are not isolated against the surrounding water, water electrolysis occurs. Oxygen and hydrogen are generated. The hydrogen emission rate for cutting 80 mm stainless steel plates is around 32,2 dm^3/min [2]. Like for the plasma cutting process, these emissions have to be controlled by using an exhaust system at the water surface, to dilute the volumetric percentage to a secure value.
An overview of the generated gaseous emissions for thermal cutting technologies under water is presented in table I.

Table I: Gaseous emissions for cutting stainless steel plates [2]

	Material thickness [mm]	NO [dm^3/min]	NO_x [dm^3/min]	CO [dm^3/min]	H_2 [dm^3/min]
Plasma Arc cutting	50	1,9E-02	2,0E-02	<2E-2	9,4
	80	2,9E-02	3,0E-02	<2E-2	12,3
CAMC-cutting	50	8,0E-03	9,0E-03	25,7	39,7
	80	8,0E-03	9,0E-03	31,2	32,2

AWSJ cutting does not produce any gaseous emissions.

Typically the exhaust air from the thermal cutting processes used for segmentation of RPV or RVI are collected and filtered by specific temporary exhaust air systems. These systems should be connected to the plants stationary off gas system to ensure the following:

- A proper overall balance of aerosol activity and air flow according to the plants license requirements
- Allow control interlocks for operational and emergency shut down procedures for both systems
- Ensure a controlled air exchange rate above the water at the working area
- Minimise the impact on the plants internal air flow balance and staggered air pressure system

Beside gaseous emissions the cutting power of each technology has to be compared. A well established parameter to compare cutting technologies is the cutting speed or feed rate for different materials and thicknesses.

Table II: Feed Rate for Plasma Arc cutting and AWSJ for different wall thicknesses

wall thickness [mm]	30 mm	50 mm	70 mm	115 mm
Plasma Arc feedrate [mm/min]	460	120	80	30
AWSJ feed rate [mm/min]	85	50	31	12

Data from table II have been taken from work performed by NUKEM Technologies staff during dismantling projects at MZFR, Karlsruhe and VAK, Karlstein. The data of Plasma Arc have been

generated at water depth of 1 m. Parameters like current, type of nozzle and electrode have been set to the optimum for each purpose.
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 CAMC feed rate is significantly below the one of Plasma Arc cutting and AWSJ. A stainless steel plate of 700 mm length and an increasing wall thickness from 70 to 125 mm can be cut at a feed rate of approx. 4 mm/min. This can be seen as another reason why CAMC is not established as main cutting technology for RVI dismantling but very helpful for lots of specific cutting situations.

The recoil power of the water jet produced by the nozzle is relatively small allowing a lean design of the required manipulator. During Mock up testing it was shown that according to the recoil power, the positioning precision and the repeat accuracy manipulators for Plasma Arc cutting are also suitable for AWSJ cutting and vers visa. Manipulators for AWSJ additionally have to take into consideration the possible spread of abrasive.

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 „defence 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.

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.

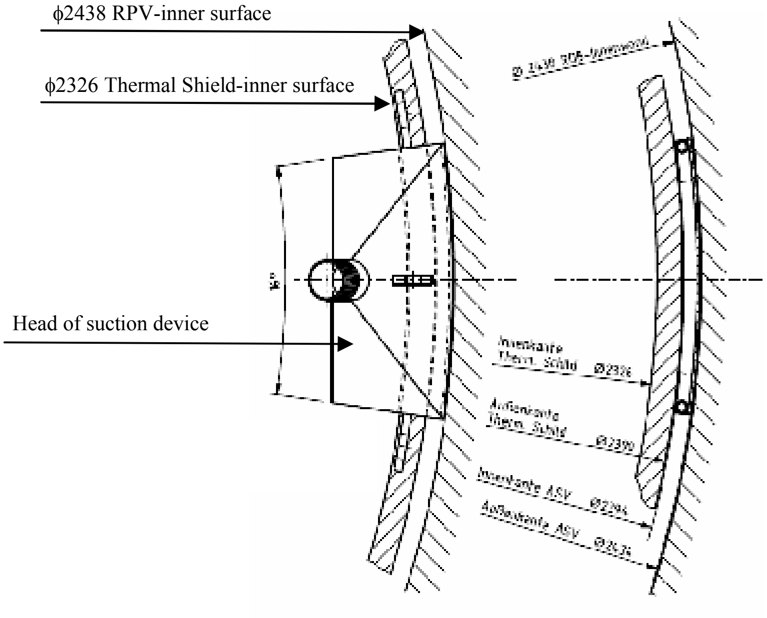

Fig. 6: Geometric situation of Thermal Shield and RPV at VAK

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 “defence in depth” transferred from reactor design to reactor dismantling.

Performing the job it turned out that it was possible to cut the Thermal Shield even without scratching the RPV cladding.

CONCLUSION

The presented cutting technologies Plasma Arc cutting, Contact Arc Metal cutting and Abrasive Water Suspension Jet 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, these limits have been exceeded with each “hot use” in the past and will further exceed in the future. First tests on CAMC for high wall thicknesses have been performed, high pressure pumps and related technology for AWSJ have been improved during the last years.
Additionally the approach during design and mock up process can be a source for high sophisticated application of existing technology.

REFERENCES

[1] Pfeifer, W.; Bienia, H.; et al.: Plasma cutting in the Multi-purpose Research Reactor (MZFR) – Underwater use at steel thickness of up to 130 mm. Welding in the world – Journal of the international Institute of Welding. Volume 51, No. 11/12 – 2007. ISSN 0043-2288

[2] Priesmeyer, U.: Thermische Schneidverfahren und Werkstoffreaktionen im Hinblick auf die Entstehung von Staub und Aerosolen, Fortschritt-Berichte VDI, Reihe 2: Fertigungstechnik, Nr. 450, ISBN 3-18-345002-X, 1997

[3] Bach, Fr.-W.; Bienia, H., et al.: CAMX – Thermische Hochleistungstrennverfahren für den Einsatz unter Wasser. Atw – International journal for nuclear power, No. 4, INFORM GmbH, Berlin, April 2002

[4] Steiner, H.: Partikelmeßtechnik beim Plasmaschmelzschneiden, Fortschritt-Berichte VDI, Reihe 2: Fertigungstechnik, Nr. 245, ISBN 3-18-144502-9