LD-SAFE

Laser Dismantling Environmental and Safety Assessment

Guideline - use of laser cutting in reactor dismantling environment

Deliverable D3.5

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1. INTRODUCTION

1.1. Background

For dismantling of radioactive components during nuclear decommissioning, the use of laser technology has, so far, been relatively limited. For this reason, laser cutting as an option for reactor dismantling has been explored in the Laser Dismantling Environmental and Safety Assessment (LD-SAFE) project. LD-SAFE is a four-year European research and innovation project with the aim of demonstrating that laser cutting technologies are effectively operational for the dismantling of the most challenging components of nuclear reactors.

During LD-SAFE, a wide range of experiences and lessons learned have been gained from assessments, experiments and demonstrators of both in-air and underwater laser cutting. These guidelines reflect those experiences and lessons learned as a means to support future end users during implementation of laser cutting in dismantling of boiling water reactors (BWRs) and pressurized water reactors (PWRs).

1.2. Objective

The objective of this document is to assist in planning for installation, operation and removal of the laser cutting system in regard to cutting of radioactive components during dismantling of BWRs and PWRs. The guidance notes are intended for the following users:

- Organizations that are exploring laser technology as an option for cutting of reactor components and are looking to learn about the safety aspects to facilitate selection of a cutting technology.
- Organizations that have decided to implement laser technology for cutting of reactor components and need input on the safety aspects that need to be considered.

1.3. Scope

These guidelines encompass key aspects that need to be considered prior to using the laser cutting system demonstrated in the LD-SAFE project in a nuclear reactor dismantling context. The guidelines take into account a broad range of experiences gained throughout the project from both in-air and underwater laser cutting.

The scope of this document includes safety aspects that are unique to the use of laser technology. General considerations that apply for all types of cutting technologies are not addressed, such as ensuring that use of the technology is compliant with the licence and that emissions are monitored.

This document addresses the process equipment part of the laser cutting system, whereas the manipulator[1] generally is out of scope. Guidance related to loss of services and other anticipated operational occurrences are included (see Section 8.7), as well as guidance on how to avoid accidents. How to mitigate or resolve various scenarios if an accident has occurred is, however, beyond the scope of this document.

These guidelines have been developed for laser cutting of reactor pressure vessels[2] and reactor vessel internals in BWRs and PWRs. They may also be of use when considering adopting the laser cutting system for dismantling of other components or in other types of facilities.

2. REFERENCES

1. *Generic Safety Assessment,* LD-SAFE Deliverable D4.3, Reference No. CN-LD-SAFE-12584-DEL-146694-EN, Revision B, August 28, 2023.

3. ACRONYMS

BWR	Boiling Water Reactor
HEPA	High-Efficiency Particulate Air
HMI	Human-Machine Interface
LD-SAFE	Laser Dismantling Environmental and Safety Assessment
PWR	Pressurized Water Reactor

4. MAIN SAFETY ISSUES WITH LASER CUTTING OF REACTOR COMPONENTS

Like any work associated with dismantling of radioactive components, great care needs to be taken when installing, using and removing equipment for laser cutting. For the most part, the hazards associated with laser cutting are similar to other cutting technologies, but three main safety issues have been identified for laser cutting of reactor components:

- Residual laser beam power (for in-air cutting only), see Section 8.3.
- Generation of aerosols (for in-air and underwater cutting), see Section 8.4.
- Generation of hydrogen gas (for underwater cutting only), see Section 8.5.

In addition, these guidelines address more general aspects related to the laser cutting system, to ensure that a complete view is provided of the considerations that need to be taken for safety.

[1] Several types of manipulators can be used for dismantling of a nuclear reactor, as long as they meet the laser cutting system specifications (for example, payload and speed).

[2] The LD-SAFE project concluded that thicknesses beyond 200 mm in air and 80 mm underwater is challenging to cut using current state-of-the-art technology. As such, there may be limitations on the feasibility of cutting through BWR and PWR reactor pressure vessels without further research and development of laser cutting of thick components.

5. THE LASER CUTTING SYSTEM

During laser cutting, a focused laser beam is used to locally melt the material that it hits. This thermal process is complemented with a co-axial gas jet that ejects the molten material and creates a narrow kerf. As such, there is no physical contact between the laser cutting tool and the piece being cut. Another benefit of laser cutting is that the system is remotely operated and requires little to no maintenance between cuts, so once installed, workers do not need to spend much time in the radiological work area.

The laser cutting system that has been tested within the LD-SAFE project consists of two main parts:

- The process equipment, that is, the laser cutting head (also referred to as the cutting tool), fibres, coupler, laser source, compressed air unit, water distribution unit and control unit.
- The manipulator (a remote-controlled robotic arm) that positions and moves the laser cutting head. The manipulator is, in turn, mounted on a transporter that is used to move the cutting head and manipulator to and from the location for cutting.

The laser cutting system has been designed to be versatile and can be used for both in-air and underwater cutting. In the following subsections, the main components of the process equipment of the laser cutting system are outlined, along with guidance notes for each of the components. Most of the laser cutting system's components are standard, but some are bespoke, see Table 1. The interfaces between the laser cutting system and the nuclear facility are outlined in Section 7.4.

Table 1: Standard and bespoke components of the laser cutting system.

Component	Standard	Bespoke
Laser source* (Section 5.1)	✓	
Laser fibre (Section 5.2)	✓	
Laser coupler* (Section 5.2)	✓	
Compressed air unit (Section 5.3)	✓	
Water distribution unit (Section 5.3)	✓	
Supply lines (Section 5.3)	✓	
Umbilical (Section 5.4)		✓
Laser cutting head* (Section 5.5)	✓**	
Collection system (Section 5.6)		✓
Control unit (Section 5.7)		✓

* The laser source, laser coupler and underwater laser cutting head each require a refrigeration unit, which also is a standard component.

** The laser cutting head has a standard design (developed by CEA), available via ONET Technologies only.

For each of the components it is essential to follow all the recommendations by the manufacturer. Examples of this include recommendations related to installation, preventative maintenance and when to shut down versus keep a component in a ready-for-use state.

5.1. Laser Source

The laser beam that performs the cutting is generated in the laser source. As stated in Table 1, this is a standard commercial component, and a wide range of high-power laser sources are readily available on the market for various uses.

Different values of laser power can be used for the laser cutting system, and the power can be modulated as needed. The laser source includes a refrigeration unit that provides water cooling.

Guidance regarding the laser source includes:

1. Access to the laser source should be restricted to qualified personnel only.
2. The laser source should be installed in a manner that ensures protection from the elements, including protection from humidity and extreme temperatures.
3. The laser source should be installed on an anti-vibration mounting to reduce risk of vibrations.
4. A coloured stacked light should be installed to warn when the laser source is in use.
5. The shelter in which the laser source is stored should be labelled with a 'laser hazard' sign and be locked during laser cutting.
6. The laser source should be drained from water annually or when not in use for longer periods of time, to ensure that water quality is maintained. The laser source should also be drained prior to being lifted, transferred on site or transported off site.

5.2. Laser Fibre and Coupler

The laser fibre is an optical fibre through which the laser beam is transmitted from the laser source to the cutting head. For dismantling activities, the laser propagates through two fibres[3], which are connected using a laser coupler that transmits the laser beam between the two sections with minimum power loss. There are two main reasons for using multiple laser fibres and associated coupler:

- Using different laser fibres in radioactive and non-radioactive areas, which facilitates replacement if the fibre is damaged and enables reuse of the laser fibre located in non-radioactive areas.
- Enabling longer distances between the laser source and the laser cutting head (100 m is typically the maximum length of a laser fibre).

[3] For cold testing, one laser fibre may be sufficient.

The laser coupler is water cooled by a dedicated refrigeration unit (that is, not the same unit as for the laser source).

Guidance regarding the laser fibres and laser coupler includes:

1. To prevent damage to the laser fibre, bending and twisting should be in accordance with the recommendations by the manufacturer (note: optical fibres are not as flexible as, for example, electric cables).
2. The laser fibre should be protected from physical damage, such as crushing, squeezing, shocks and tearing.
3. In outside passageways, the laser fibre should be protected (using a cover) from extreme weather conditions (temperature, humidity, etc.) as well as from rodents and other animals.
4. The fibre path should be physically separated from other utilities.
5. The fibre path should be properly identified and clearly labelled.
6. The laser fibre should be manually connected to the laser coupler in a carefully controlled clean environment. Additional precautions that should be taken to avoid dust settling on a section include: a) removing the fibre from its protective wrapping only right before mounting in the coupler, and b) pointing the fibre end toward the ground, when possible.
7. The laser coupler should be installed in a manner that ensures protection from the weather, including from humidity and extreme temperatures.

5.3. Compressed Air Unit, Water Distribution Unit and Supply Lines

The compressed air unit provides dry air for cooling of the in-air laser cutting head, as well as assist gas for both in-air and underwater cutting. For underwater cutting, cooling is provided by a water distribution unit. Instead of using a dedicated unit for this purpose, the cooling system of the laser coupler can be used to also fulfil the function of cooling the underwater laser head.

The compressed air and cooling water are transferred to the laser cutting head via dedicated air and water supply lines. The guidelines regarding the air and water supplied to the laser cutting head include:

1. A pneumatic skid should be used to control flow rates, temperatures and humidity, etc. Pressure regulators should also be included to manage flow rates. Flow rates should be adjustable and controlled from the laser human-machine interface (HMI).
2. The cooling water in the water distribution unit and supply lines should be in a closed circuit (to avoid risk of contaminating the water inside the circuit).

5.4. Umbilical

For underwater cutting, an umbilical contains the laser fibre, compressed air and water supply lines and instrumentation & control links in order to keep them dry.

For in-air cutting, the need for an umbilical (to mainly protect the laser fibre and supply lines from hot sparks) depends on the dismantling environment.

The safety considerations for the umbilical are the same as for the laser fibre and supply lines (see Section 5.2 and Section 5.3, respectively). Additional safety considerations for the umbilical are:

1. The umbilical should be designed to fit with the minimum bend radius of the laser fibre.
2. The umbilical should be guided inside the cutting area so that it cannot be overstretched or twisted as the robotic arm moves.

5.5. Laser Cutting Head

There are two different laser cutting heads for the laser cutting system: one for in-air cutting and the other for underwater applications. In both cases, the cutting head contains optical elements that channel the laser beam to a degree that enables cutting. The laser beam exits the cutting head via a nozzle. Pressurized airflow is supplied through this nozzle to blow out molten material from the piece that is being cut. For in-air cutting, the dry airflow is also a coolant for the tool and serves to prevent pollutants from entering into the equipment.

For the underwater laser cutting head, the principle is the same, but the airflow is also used to create a dry cavity between the tool and the work piece to allow the laser beam to propagate in air. The underwater cutting head includes a waterproof envelope, and its optical elements are water cooled.

The principles of both in-air and underwater cutting are shown in Figure 1.

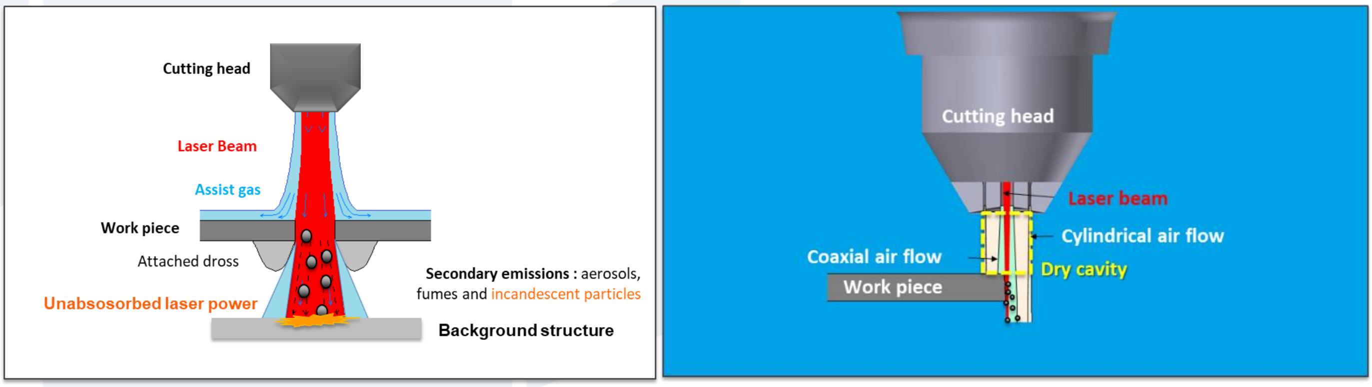


Figure 1: The principles of in-air cutting (on the left) and underwater cutting (on the right).

The operation parameters of the system are determined by the thickness and nature of the piece that will be cut, while taking into account the structures behind it. The variable operation parameters include:

- Laser power.
- Cutting speed.
- Distance between the nozzle and the piece to be cut (the “stand-off”).
- Angle.

The wavelength of the laser is, however, fixed in infrared light between 1030 and 1070 nm. As such, it is invisible to the naked eye.

Triggering the laser beam requires manual, continuous and deliberate action from the operator. That is, the laser beam does not automatically exit the laser source, and if the trigger is stopped, the laser beam is switched off.

There are no wear parts in the laser cutting head, which means that the tool has very high availability (as was confirmed during the LD-SAFE demonstrator). The laser cutting head is also robust, so that it avoids being damaged in case it collides with any items along its trajectory.

Guidance regarding the laser cutting head includes:

1. For underwater cutting, the shutter should always be closed unless the assist gas is flowing (to avoid risk of water entering the laser cutting head). In the event of loss of compressed air during underwater cutting, the shutter should, therefore, be closed.

5.6. Collection System

During laser cutting, having provisions for collection of aerosols, dust and fumes is recommended. There are various options for such a collection system. For in-air cutting, aerosols generated during cutting can be managed using two different configurations (both can be applied at the same time):

- Laser cutting in a confined enclosure with overall filtration of the area where the cutting takes place; this has the following consequences in terms of contamination:
    - Decontamination (removal of particle deposits) in the area within the confined enclosure is required once cutting operations have been completed.
    - The level of airborne contamination initially increases during laser cutting but subsequently stabilizes.

- Laser cutting with a local collection system; this has the following advantages:
    - Particles generated are captured as close as possible to the cutting point.
    - The collected materials are effectively contained.

For in-air cutting, the local collection system can be integrated with the overall laser cutting system and then consists of a collection head for aerosols, collection lines and a first level of aerosol capture (for a certain diameter of particles), see Figure 2.

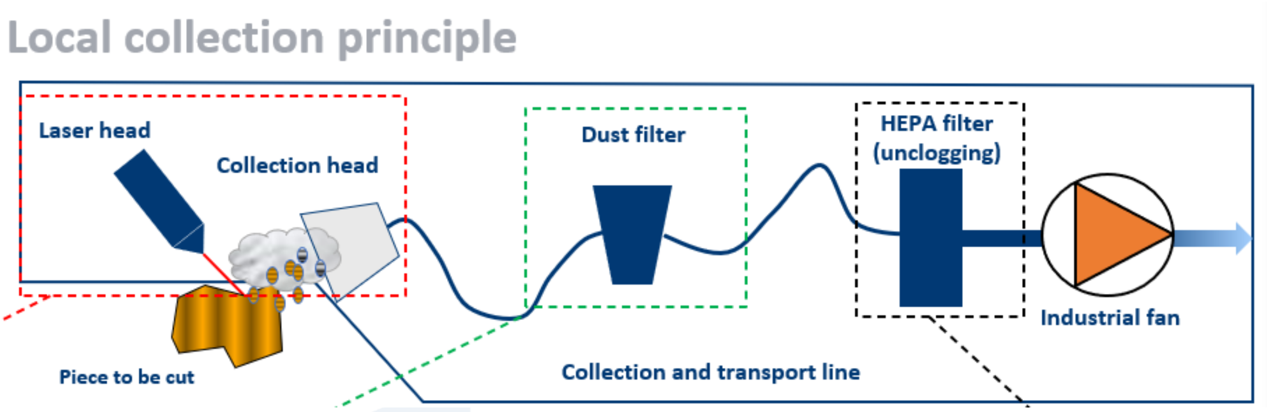


Figure 2: Principle for a local collection system for aerosols, dust and fumes during in-air laser cutting.

5.7. Control Unit

The laser cutting system is remote-controlled, using multiple cameras and screens that provide the operators with a clear view of the cut from different angles. Guidance regarding the control unit includes:

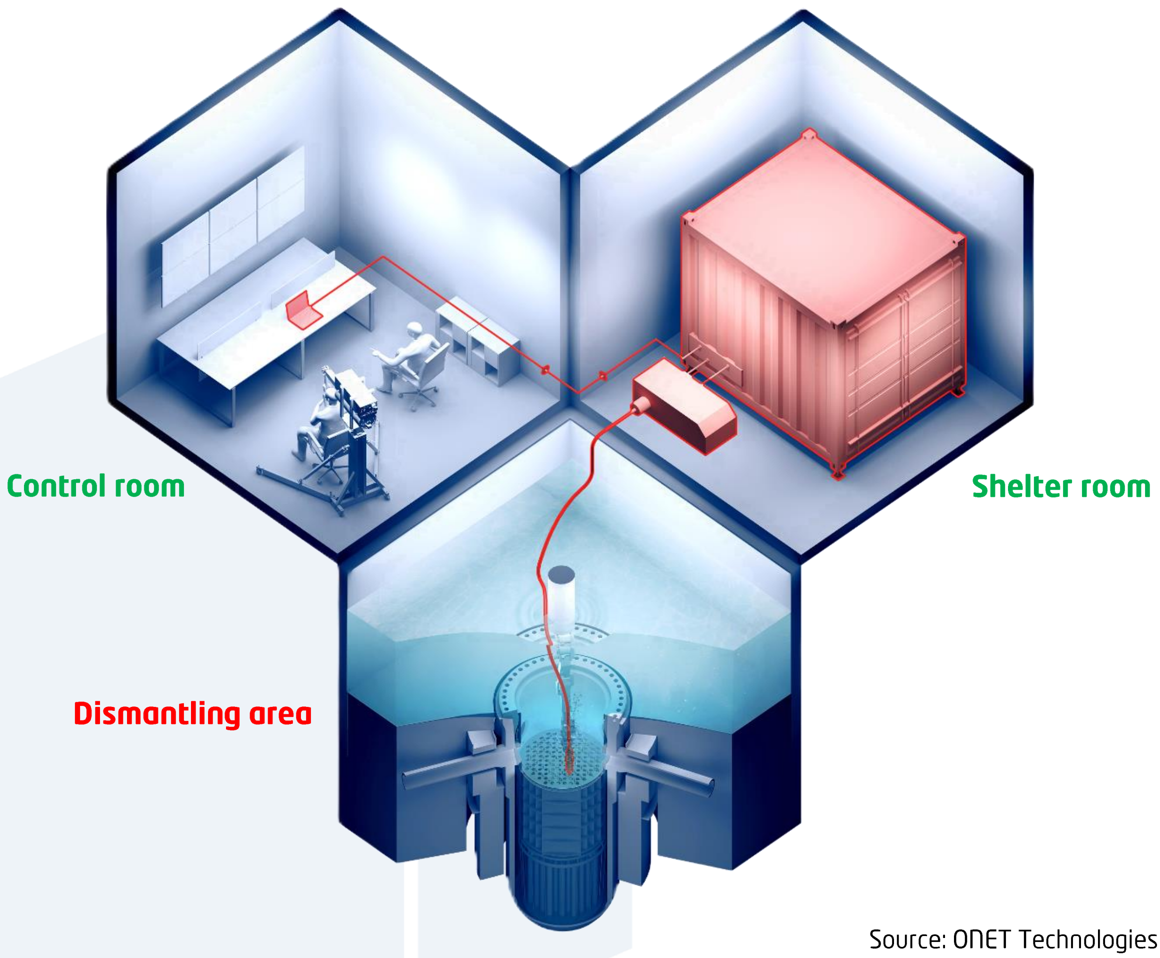
1. Human and organizational factors should be considered for the control room and conditions where the control unit will be located (see Section 6).
2. HMI aspects for consideration should include but not be limited to the number of cameras and lights that will be used, the number and size of the screens for displaying the remote cutting operations and the positioning of the operators in the room.

6. MAIN AREAS HOUSING THE LASER CUTTING SYSTEM

To facilitate operation and maintenance, and minimize radiation dose to workers, the equipment of the laser cutting system is separated and located in three main areas:

- **Shelter room** – where the laser source, utilities and instrumentation & control equipment is located.
- **Dismantling area** – where the laser cutting occurs.
- **Control room** – where the operators of the laser system are located.

The laser coupler is located in an interface zone between the shelter room and the dismantling area.



Source: ONET Technologies

Figure 3: The three main areas and the associated equipment for the laser cutting system.

The areas above are not necessarily different physical rooms, especially for the utilities where some equipment can be located outdoors.

From the laser source to the control room there are no significant distance constraints other than the length of the cables that are linking the two. But from the laser source to the cutting head:

1. The total distance (for standard optical fibres) should be below two hundred meters to avoid scattering in the fibre and subsequent damage to the equipment. (This would involve two optical fibre sections, as the current maximum fibre length is 100 m.)

In the following subsections, additional details are provided for each of the three main areas.

6.1. Shelter Room

The shelter room houses major equipment of the system, such as the laser source, compressed air unit and refrigeration unit, and it provides the necessary utilities to keep the equipment running. This room is normally not staffed, but is accessed by operators as needed, for inspection and maintenance. The shelter room:

1. Should be located at a distance of up to 200 m from the dismantling area.
2. May have some of its equipment located in a shelter outdoors, such as the laser source.

6.2. Dismantling Area

The dismantling area is where the laser cutting head and the manipulator are located, as well as parts of the umbilical (which contains the laser fibre and supply lines to the cutting head).

6.3. Control Room

The control room hosts all control systems related to the use of the system, namely the equipment to control the laser cutting and the visualization tools (screen, camera feeds, etc.), as well as the control equipment for the manipulator. The control room:

1. May be located far away from the dismantling area (there are no limitations on this distance).
2. Should be staffed by a minimum of two people during cutting operations.

7. PLANNING AND PREPARING FOR LASER CUTTING

7.1. Limitations of the Laser Cutting System

The laser cutting system can be used to cut a wide range of materials, thicknesses and geometries. At present, the system's limitations include:

- **Material** – Most types of materials can be cut using the laser cutting system, including but not limited to stainless steel, carbon steel, titanium, graphite and several types of ceramics.
- **Thickness** – Steel and stainless steel of thicknesses up to 200 mm can be cut with 14 kW laser power in air, see Table 2. For underwater cutting, thicknesses up to 80 mm can be cut (the laser power range for underwater cutting is 8-16 kW), but tests during the LD-SAFE demonstrator have indicated that thicknesses of up to 100 mm might be possible to cut in certain configurations.
- **Layers** – In air, multiple layers can be cut, but tests performed during the LD-SAFE project indicate that, underwater, only single layers of materials are possible to cut due to attenuation of the laser by the water.
- **Water depth** – The underwater laser cutting head has been tested down to a water depth of 5.6 m; a minimum of 3 m water depth is recommended for radiation shielding.

Table 2: Maximum material thickness for in-air laser cutting.

Configuration	Material	Thickness (mm)	Laser Power (kW) vs Cutting Speed Limit (mm/min)			
			4	8	10	14
In-Air	Steel and Stainless Steel	20	175	350	500	700
		40	20	125	150	225
		60	-	40	55	120
		100	-	7.5	25	50
		120	-	-	8.5	32.5
		200	-	-	-	2.5

7.2. Comparison of In-air and Underwater Laser Cutting

When comparing in-air and underwater laser cutting, some key differences are:

- The in-air laser cutting head has higher tolerance (a few cm) in terms of positioning, compared with underwater cutting.

- Underwater cutting has the advantage of water acting as a radiation shield but requires water filtration to be operational during cutting (using an existing water treatment system or a new, dedicated system).
- Risks associated with residual laser power and release of aerosols are higher when cutting in air.

7.3. Safety Assessment and Licensing

The regulatory regimes and requirements regarding nuclear decommissioning vary vastly between different jurisdictions. As such, it is not possible to provide specific guidance regarding safety assessment and licensing for reactor dismantling using laser cutting, other than to state that it needs to be ensured that all requirements are met and that the necessary approvals are obtained prior to commencing installation of the laser cutting system.

As input to the user's safety assessment and licensing related to the laser cutting system, the LD-SAFE project has produced a *Generic Safety Assessment* [Ref. 1]. Regarding the general use of lasers, the European Union has standards and directives, but national laws also exist.

7.4. Interfaces with the Nuclear Facility

The laser cutting system mainly consists of standard components (see Table 1), but it might need to be adapted for specific applications. The user of the laser cutting system needs to ensure compatibility between the existing systems of the facility and the requirements of the laser cutting system, including specifications for utility power and fluids, as applicable.

The laser cutting system requires access to a wide range of systems and programs already in place at the nuclear facility. Examples of this include but are not limited to:

- General management processes and procedures, such as quality assurance, training and records management.
- Electrical power (total needed for the laser cutting system (installed capacity) is approximately 100 kVA).
- Compressed air (can be the same as the facility's air, if it meets the laser cutting system air quality requirements (class 1.3.1 following ISO 8573-1: 2001)).
- Breathing air.
- Cooling water.
- Demineralized water.

- Water filtration (for underwater cutting); normal plant systems can be supported by supplementary clean-up systems.
- Ventilation (including filters that have capabilities for capturing aerosols).
- Radiation protection (including area radiation monitoring in the reactor building and process radiation monitoring (that is, monitoring of radiation in ventilation, water, etc.)).
- Fire protection (detection and mitigation systems within the building; reactor building spray system or area sprinklers).
- Environmental monitoring.
- Emergency preparedness.
- Cranes and other handling equipment.
- Workshop for active components.
- Radioactive waste management.
- Access control.
- Communication.

Guidance regarding the interfaces between the laser cutting system and the nuclear facility includes:

1. Users of the laser cutting system must specify all interfaces with their respective facility and ensure compatibility between the existing facility systems and the requirements for laser cutting. This includes any passage from containment to other areas, which should be subject to plant specific design and operational requirements, as for other containment penetrations.
2. The interface with the ventilation must be such that the laser system will stop automatically upon loss of ventilation, supported with alarms for manual stop, if needed.
3. Users must ensure that their off-site emergency plan will not require any modifications due to the installation and operation of the laser cutting system. If applicable, users must reassess the accident scenarios postulated in the safety assessment of the facility and revise the emergency plan accordingly.
4. For underwater cutting, pool water chemistry and visibility must be checked and confirmed that they conform to the requirements of the laser cutting system.
5. Security aspects, including cyber security, must be addressed before commencing laser cutting.

7.5. Planning of Segmentation and Waste Packaging

Like any type of cutting during reactor dismantling, a segmentation plan needs to be developed as part of planning and preparing for laser cutting. One of the advantages of laser technology is the flexibility that it provides, so that pieces can be cut in a manner that makes optimal use of the waste package volume. Laser cutting, therefore, has the potential to reduce the overall number of waste packages compared with other cutting technologies. Given this:

1. Operators should be trained in the benefits of laser cutting when it comes to the cutting of complex geometries, so that waste packages can be filled in an optimal way.
2. Procedures should be developed to guide workers in planning segmentation and waste packaging in a manner that ensures that the benefits of laser cutting are utilized and, consequently, the number of resulting waste packages are minimized.

7.6. Operator Training

Similar to any type of dismantling activities, the operators who will be performing laser cutting need to be trained on the specific system and procedures that they will be using. Operator training is a vital aspect from an organizational and human factors perspective. Guidance regarding operator training includes:

1. The operator training for laser cutting should be part of the facility's integrated management system and be subject to the same requirements as other operator training for dismantling at the facility.
2. The operator training must include but not be limited to:
    - General laser safety training.
    - Use of the laser cutting system (including use of the manipulator).
    - Procedures if malfunctions occur, including loss of ventilation, loss of power, etc.
3. All staff with access to the dismantling area must be aware of the general laser risks.
4. The trainer must be certified for conducting laser training.

As part of the end user support of the laser cutting system, training will be possible to obtain from ONET Technologies.

7.7. Installing the Laser Cutting System

The laser cutting system has been designed to facilitate and reduce the time required for installing the system. General guidance regarding installation is as follows (for further guidance on specific components of the system, see Section 5):

1. Guidance from the respective manufacturer of the different components must be followed.
2. Personal protective equipment must be used in accordance with the facility's requirements in the respective work area.
3. The robotic arm must be selected to ensure that the required accuracy can be achieved when equipped with the laser cutting head.
4. For installation of the two shelters (containers) that house the laser source and the compressed air unit, respectively, a crane with capacity for heavy loads must be selected for lifting the shelters into position. When performing these lifts, high winds or other poor weather conditions should be avoided due to the high precision needed for the positioning of the shelters.
5. For the shelter that houses the laser source, ground support (a distribution plate) should be added to ensure that the load of the shelter is evenly distributed and that the shelter's position is flat.
6. Since the laser source is equipped with a nitrogen bottle, sensors for monitoring nitrogen and oxygen levels should be included in the laser source shelter.
7. If the laser source has previously been used at a different location, the laser source manufacturer should perform a new commissioning process to ensure that the optical chain is well calibrated.
8. A specific circuit breaker for electrical protection of the laser source may be needed to meet the requirements of the manufacturer.
9. When installing the laser fibre, it should be laid down with its dedicated protection on the connectors (as such, the wall penetrations should be much larger than the actual width of the laser fibre). For the passageways, stickers or other visual markings that indicate the presence of "LASER" must be provided on the laser fibre, in accordance with the manufacturer's instructions.
10. To reduce risk of twisting or bending the laser fibre beyond its minimum bend radius (see Section 5.2) during operation of the system, the installation of a mechanical support on the umbilical should be considered.
11. For underwater cutting, the umbilical should be pressure tested as part of installation.
12. To protect the cavity liner in case of heavy load drop or residual power issues, a protective cover should be installed on the floor of the cavity.

13. For underwater cutting, sufficient water treatment of the pool water must be ensured to reduce contamination levels in the water and ensure good visibility during operation – by installing a system that includes filtration of dust, metal chips and other particles and/or by testing an existing water treatment system to confirm that it has the required capacity. The water treatment system(s) should be located as close as possible to the cutting area.

14. Installation of localized ventilation should be considered to minimize the spread of contamination. Preferably, the local ventilation system should be equipped with pre-filtration to reduce risk of the high-efficiency particulate air (HEPA) filter becoming clogged.

15. To avoid risk to workers located outside of the dismantling area, it must be ensured that the area where cutting will take place complies with the laser regulations regarding "light tightness".

7.8. Preparing for Each Laser Cut

Once the laser cutting system has been installed and commissioned, the following guidance is provided when preparing for each individual cut:

1. The specific operation parameters (see Section 5.5) must be determined before every cut to minimize the risk of residual power scenarios and ensure that the cutting process is robust.

2. Cutting should generally start at the top of the structures that are being cut and then move downwards (due to the lack of clearance inside the reactor pressure vessel).

3. Fully vertical cuts with the cutting head pointing upwards should be avoided, since it would risk ejected particles to fall onto the equipment and cause damage outside the cutting area.

4. The cutting speed should be the fastest speed possible, to reduce risk of residual power impacting background structures, without reducing the robustness of the cutting process.

5. The stand-off should be between 10 and 50 mm for in-air cutting and between 5 and 15 mm for underwater cutting.

6. If the system is to be moved, the water in the cooling circuit should first be purged of water.

7. An evaluation should be made prior to each cut regarding the background structure and the consequences if it is damaged due to residual power scenarios (that is, risk of loss of structural integrity, load drops, etc.)

8. An evaluation should be made of the planned umbilical trajectory to ensure that it will not get caught or bent beyond the minimum bend radius.

9. To de-risk complex cutting configurations, cutting tests may be done in a mock-up before laser cutting in the dismantling area is performed to ensure that the optimal parameters have been set.

10. The absence of any combustible materials in the laser beam's direction should be confirmed, to avoid risk of accidental ignition.

11. It must be ensured that the equipment can be positioned in accordance with the selected stand-off and angle throughout the trajectory of the cut (that is, that the manipulator and cutting head have access to the piece being cut and are not blocked by other items on their trajectory); if needed, items that are in the way must be removed.

12. Before starting a cut, compliance with the requirements pertaining to laser safety must be ensured (for example, requirements on access control and confirmation that no persons are present in the area).

8. PERFORMING LASER CUTTING

8.1. Operating the Laser Cutting System

During cutting, the laser cutting head moves along the piece to be cut and generates a kerf. As part of this, some material is released into the environment as incandescent particles, dust, fumes and aerosols, see Figure 4. Most of the released material agglomerates and solidifies on the edge of the cut on the rear side of the piece, that is, forming attached slag.

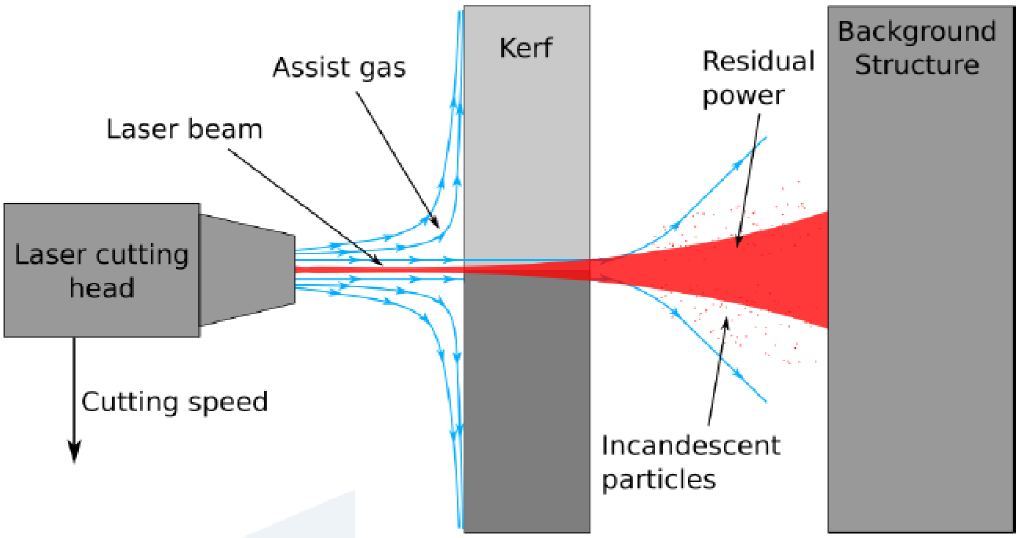


Figure 4: Laser cutting through a piece, creating a kerf and the release of incandescent particles.

In the control room, a range of emergency stop buttons are available (both manual and automatically triggered), in the event that anything unexpected or potentially damaging to equipment or surrounding structures occurs; the emergency stops include but are not limited to stopping the laser cutting system if:

- Cables are accidentally cut.
- Rupture on the laser fibre is detected (by electrical sensors in the fibre).
- Differential pressure in the ventilation filters is lost.
- Temperature is too high in the laser cutting head (as it risks damaging the optical lenses).
- Abnormal sensor indications occur in the fluid distribution (such as temperature or pressure changes).
- Fire or smoke is detected.
- Elevated dose rates or contamination levels are detected outside the confinement area.

General guidance regarding operation of the laser cutting system is as follows (for further guidance on specific components of the system, see Section 5):

1. During cutting, the control room must be staffed with a minimum of two persons (an operator and a supervisor) to enable verifications during operation.
2. Operation of the laser cutting system should be based on a laser risk analysis.
3. Areas that risk being pointed at by the laser beam must have no persons present while the laser is in use.
4. To avoid damaging the laser fibre during operation, the laser fibre should not be bent or twisted beyond the recommendations of the manufacturer (see Section 5.2).
5. For ventilation control, laser cutting should be performed in areas with negative pressure (similar to other activities that risk the spread of contamination).
6. During underwater cutting, risk of the laser inadvertently rising above the water must be avoided. For this reason, the movements of the manipulator must be limited (for example, by end-of-line switches on the bridge so that the arm cannot be raised too far).
7. During underwater cutting, water levels should be monitored, and an alarm should signal if a water level drop is detected.
8. For underwater cutting, operating procedures should be developed to state that the power to the laser will automatically be cut in the event of loss of ventilation or loss of water filtration.

9. The emergency stop of the laser should be such that it only shuts off the transmission to the laser cutting head – not the power to the laser source.

10. The accuracy of the amount of power delivered by the laser source and the laser cutting head must be checked regularly (using a calorimeter).

8.2. Heat

During laser cutting, most of the laser power is converted to heat in the material that is being cut. Regarding the heat:

1. If cooling of the laser cutting head stops during cutting, the laser cutting system must be stopped to avoid risk of overheating and damaging the laser cutting head.

2. A sufficient ventilation flow should be maintained during cutting operations.

3. The ventilation system should be equipped with monitoring of the air temperature, as well as a spark arrestor in the ventilation houses (for fire safety).

For underwater cutting, heating of the pool water is not deemed to require any special provisions, provided that the water volume is sufficient to dissipate the heat from the laser cutting.

8.3. Laser Beam Residual Power

During laser cutting, only part of the laser beam's power is absorbed by the piece that is being melted and cut through. The remaining, unabsorbed laser power (referred to as residual power) continues to propagate after the cut until it reaches the structures that are located behind the cut piece. Those background structures risk being weakened or damaged by the heat that the residual power converts to when reaching those structures.

The risk of damage that can be caused by the residual power depends, among other things, on the laser power and the distance to the background structures.

Risk associated with residual power only needs to be considered for in-air cutting, whereas for underwater cutting, the residual power is attenuated by the water and diffused by particles or bubbles that are between the cut piece and the background structures.

Guidance regarding laser beam residual power for in-air laser cutting includes:

1. The cut should be planned so that the risk of residual power causing damage to background structures is minimized, by ensuring that there is a sufficient distance between the cut piece and the background structure.
2. Particular care should be taken during initiation and ending of the cut, since all the power is deposited in one location before the manipulator starts moving and once it has stopped.
3. The cut may be preferrable to test in a mock-up before laser cutting in the dismantling environment.

8.4. Release of Airborne Particles

To avoid the spread of aerosols, dust, fumes and particles that are released from the pieces being cut, it is key to have efficient systems in place throughout the cutting process to capture these releases. Preliminary design options for implementing static and dynamic confinements to avoid dispersion of contamination into the reactor building are included in the *Generic Safety Assessment* [Ref. 1].

During in-air cutting, the laser cutting system can include a local collection system adjacent to the laser cutting head (see Section 5.6). Guidance regarding this system includes:

1. The aerosols, dust, fumes and particles collected should be drawn into a dedicated air filtration unit, located adjacent to the area where the cutting occurs.
2. Exhaust from the air filtration unit should be led into the active ventilation system for the building, for further filtration, monitoring and release to the atmosphere, in accordance with standard practices at the facility.

During underwater cutting, the aerosols release is reduced by means of water scrubbing, although indications during the LD-SAFE demonstrator are that the scrubbing effects are quite limited for the releases from laser cutting. The efficiency of the scrubbing is a function of the water depth, so at greater depths the aerosol issue will be reduced. Another experience from the LD-SAFE project is that the higher the cutting speed, the lower the aerosol generation will be. To control contamination dispersion and risk of inhalation dose to workers during underwater cutting:

1. The water in the pool should be filtered continuously using a water treatment system.
2. The addition of static or dynamic confinements may be considered to capture the aerosols and feed them into the regular building ventilation system [Ref. 1].

8.5. Hydrogen Gas Generation

During underwater laser cutting of metallic materials, it is essential to ensure that generation of hydrogen gas will not pose a risk. In the LD-SAFE project, experimental evaluation of hydrogen generation risk for various cutting speeds and thicknesses have shown that very low hydrogen gas concentrations are generated, and thus, the risk of hydrogen gas generation to the degree that it could pose a risk is deemed negligible for the components within the scope of the project. To ensure that hydrogen gas generation during underwater cutting will not be an issue:

1. Laser cutting should be automatically stopped upon loss of ventilation (supported by alarms for potential manual stops).
2. Installation of a hydrogen gas sensor on the exhaust line may be considered as an additional safety measure to enable monitoring of hydrogen gas generation, although the *Generic Safety Assessment* [Ref. 1] concluded that it is not needed.
3. If underwater cutting of other materials than BWR and PWR reactor pressure vessels and reactor internals is considered (in particular zirconium alloys), then adequate evaluations of hydrogen generation must be performed and mitigative measures developed and implemented, if applicable.

8.6. Visibility

During underwater cutting, air bubbles are created from the dry air that is ejected from the laser cutting head. For this reason:

1. The water treatment system should be sufficiently efficient to reduce any visibility issues (due to air bubbles or turbidity caused by blown-out material during cutting).
2. If the air bubbles cause visibility issues, the cutting may be paused to allow bubbles to dissipate.

8.7. Anticipated Operational Occurrences

The laser cutting system has been designed to be fail safe. That is, upon loss of power, the system automatically shuts down and laser cutting is stopped. As mentioned in Section 8.1, emergency stop buttons (both manual and automatically triggered) are also available for a range of other anticipated operational occurrences. For further information regarding anticipated operational occurrences, see the *Generic Safety Assessment* [Ref. 1].

8.8. Maintenance

The laser cutting system is robust and has been designed not to require maintenance (unless damage has occurred). Guidance with regards to maintenance and repair includes:

1. If a damaged laser fibre is encountered, it must be replaced (since laser fibres cannot be repaired).
2. If the laser cutting head has been damaged, but it has not yet been used in a radioactive area and is deemed feasible to repair, it may be transferred for repair off site, at specialized facilities for lasers.
3. If the integrity of the laser cutting head has been breached and contaminants have entered into it, the laser cutting head must be replaced (since the optics inside cannot be cleaned).
4. Support systems (such as ventilation and water purification) should be maintained in accordance with the facility's standard programs and procedures.

9. ACTIVITIES AFTER LASER CUTTING

9.1. Removal of the Laser Cutting System

Once all cutting operations have been completed, the laser cutting head, manipulator and umbilical need to be decontaminated prior to removal from the dismantling area, in accordance with the facility's procedures. The parts of the system that are located in the dismantling area have all been designed to minimize contamination and facilitate decontamination.

The laser cutting head and umbilical are assumed to be discarded following use in a dismantling environment, whereas the parts of the system that are located in the shelter room and control room are intended for easy reuse at other facilities.

When handling the components of the system that are intended for reuse, the same care should be taken as when installing the system, see Section 7.7.

9.2. Waste Management

The radioactive waste that will be generated as part of laser cutting will largely be the same and require the same systems and procedures for managing the waste as the waste generated from other cutting technologies. The main types of radioactive waste that arise as a result of laser cutting include:

- Pieces resulting from the laser cutting.
- Particles, debris and, if applicable, metal pearls (from underwater cutting) fallen to the floor.
- Laser cutting head and umbilical (see Section 9.1).

- Air filters and water filters/ion exchange resins, as applicable.
- Airborne or surface contamination remaining in the dismantling area.

How to safely manage the above waste streams is beyond the scope of these guidelines, but it is not envisioned that management of the radioactive waste from laser cutting is more challenging than radioactive waste generated from other cutting technologies.

10. CONCLUSIONS

Since every reactor is unique in terms of prerequisites and characteristics, laser cutting – like other types of cutting technologies – must always be planned and prepared in detail for each case. This includes addressing all the specific risks and uncertainties at a given facility when planning and preparing for use of the laser cutting system. The guidance notes in this document can act as a starting point for such planning and preparation. Further input on the use of laser cutting technology in the dismantling of nuclear reactors is also available in the *Generic Safety Assessment* [Ref. 1], training materials and other documents that have been published as part of the LD-SAFE project[4].

As part of further developing and implementing laser technology for use in a nuclear dismantling context, knowledge and operating experience will continue to build regarding the laser cutting system. As such, it needs to be emphasized that guidance on safety of the laser cutting system will continue to be refined and augmented, also after completion of the LD-SAFE project. This document can, therefore, be viewed as a steppingstone for such further developments regarding the safety aspects of the laser cutting system.

[4] An online course on laser cutting is available on the LD-SAFE project website at https://ldsafe.eu/project-deliverable/, along with all other publicly available project deliverables.