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 is being explored in the Laser Dismantling Environmental and Safety Assessment (LD-SAFE) project. LD-SAFE is a four-year European research and innovation project that aims to demonstrate that in-air and underwater laser cutting technologies are effectively operational for the dismantling of the most challenging components of nuclear reactors.

According to the International Atomic Energy Agency's (IAEA's) general safety requirements, "decommissioning techniques shall be selected such that protection and safety is optimized, protection of the environment is ensured, the generation of waste is minimized and any potential negative impact on the storage and disposal of waste is minimized" [Ref. 1].

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 nuclear reactors. 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 more about the safety aspects to facilitate the selection of a technology for cutting.
- Organizations that have decided to implement laser technology for cutting of reactor components and need input on the safety aspects that must be considered when planning for use of this technology.

1.3. Scope

These guidelines encompass key aspects that should be considered prior to commencing laser cutting of radioactive components in a nuclear reactor, using the laser cutting system demonstrated in the LD-SAFE project. The guidelines take into account a broad range of experiences gained from in-air cutting.

Both in-air and underwater applications are covered in this document. The scope 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, that operating procedures are used and that emissions are monitored.

The scope of this document addresses the process equipment part of the laser cutting system, whereas the manipulator[1] generally is out of scope.

Guidance on how to avoid malfunctions and incidents are included but not guidance on how to mitigate or resolve if such events have occurred. Guidance related to loss of services and other anticipated operational occurrences are, however, included (see Section 8.7).

These guidelines have been developed for laser cutting of reactor pressure vessels and reactor vessel internals in boiling water reactors (BWRs) and pressurized water reactors (PWRs), but 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. *Decommissioning of Facilities*, IAEA Safety Standards Series No. GSR Part 6, Vienna, 2014.

2. *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
IAEA	International Atomic Energy Agency
LD-SAFE	Laser Dismantling Environmental and Safety Assessment
PWR	Pressurized Water Reactor

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

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 of reactor pressure vessels and reactor vessel internals. For the most part, the hazards associated with laser cutting are similar to other cutting techniques.

The main safety issues during laser cutting of reactor components are:

- Residual laser beam power (during in-air laser cutting).
- Generation of aerosols (during both in-air and underwater laser cutting).
- Generation of hydrogen gas (during underwater laser cutting).

In addition to the safety issues above, 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. One of the benefits 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.

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 that is being cut.

The laser cutting system that has been tested within the LD-SAFE project is remotely operated and enables high position tolerance for cutting of heterogeneous layers of material in air. The laser cutting system consists of two main parts:

- The process equipment, i.e., 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, while others are bespoke, as indicated in 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.

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 system includes a dedicated refrigeration unit that provides water cooling.

The laser beam has a limited range for optimum cutting (typically the distance between the laser cutting head and the material to be cut is around 10 to 50 mm for in-air cutting).

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 (in accordance with specifications provided by the manufacturer).
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.
6. To prevent damage to the equipment, the laser source should be started up regularly, shut down and kept in a ready-for-use state in accordance with the recommendations by the manufacturer.

7. Preventative maintenance should be performed annually to evaluate the state of the equipment and replace parts, if needed.
8. 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.

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[2], which are connected using a laser coupler that transmits the laser beam between the two sections with a minimum of 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).

The laser coupler is water cooled by a dedicated refrigeration unit (i.e., 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.

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

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 them 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 (in accordance with specifications provided by the manufacturer).

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. The quality of the supplied air and water should meet the specifications of the manufacturers.
2. 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).
3. 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 (see Section 5.2) and the supply lines (see Section 5.3) in order to ensure that the laser fibre and the lines are kept dry. The underwater umbilical includes compressed air supply, water supply, instrumentation and control links, and the laser fibre.

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 air cavity underwater between the tool and the work piece to allow propagating the laser beam in air. The underwater laser cutting head has a waterproof envelope around and its optical elements are cooled by water.

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

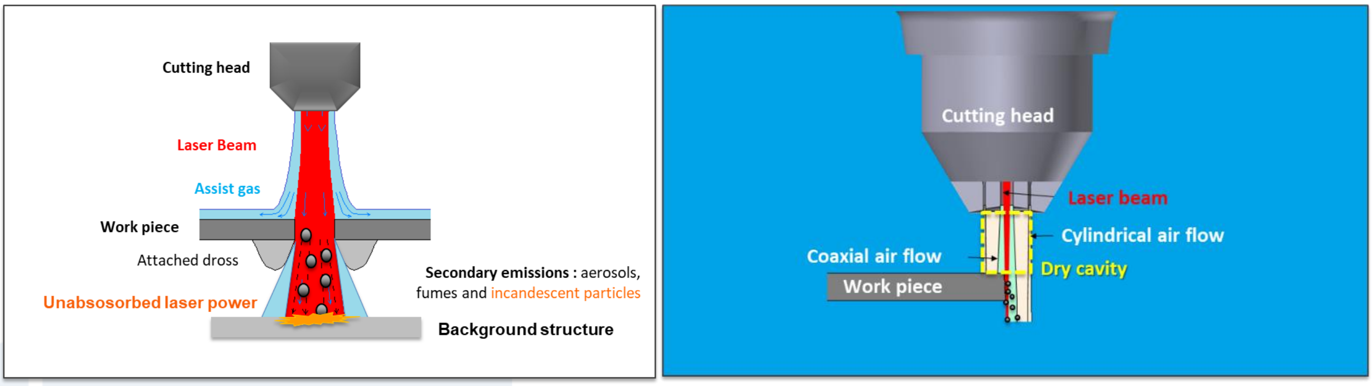

Figure 1: The principles of in-air cutting (on the left) and underwater cutting (on the right).

The laser cutting process can operate with a variable stand-off (distance between the laser cutting head and the material to be cut). Also, the users can choose the laser power and the speed suitable for their needs. 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 (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.

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).
2. For the underwater cutting head, shutters should be closed in the event of loss of compressed air.

5.6. Collection System

During laser cutting, inclusion of provisions for collection of aerosols, dust and fumes are recommended. There are various options for the 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):

1. 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.
2. 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.

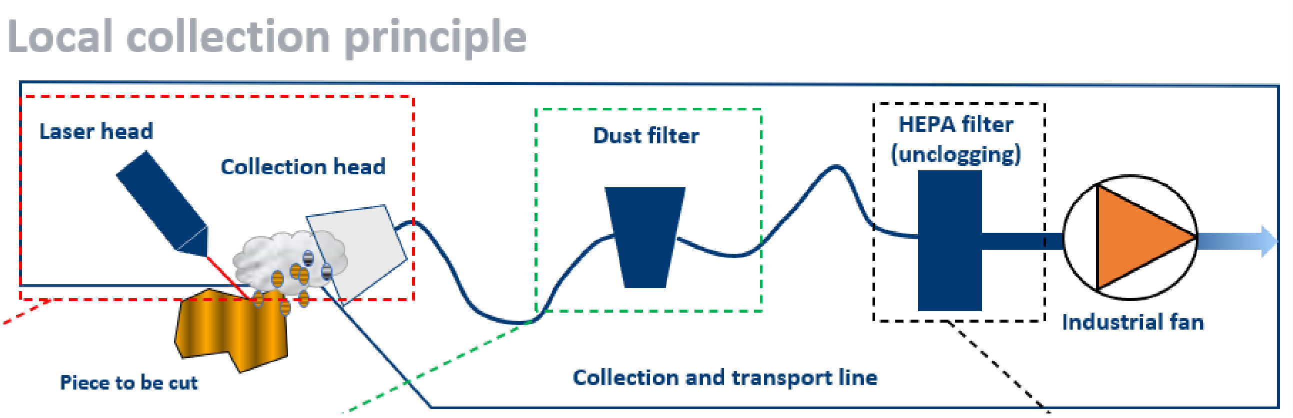

Figure 2: Principle for a local collection system for aerosols, dust and fumes during in-air laser cutting.

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 electrical control & instrumentation equipment is located.
- **Dismantling area** – where laser cutting occurs (dose rates and contamination levels are typically high in this area).
- **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.

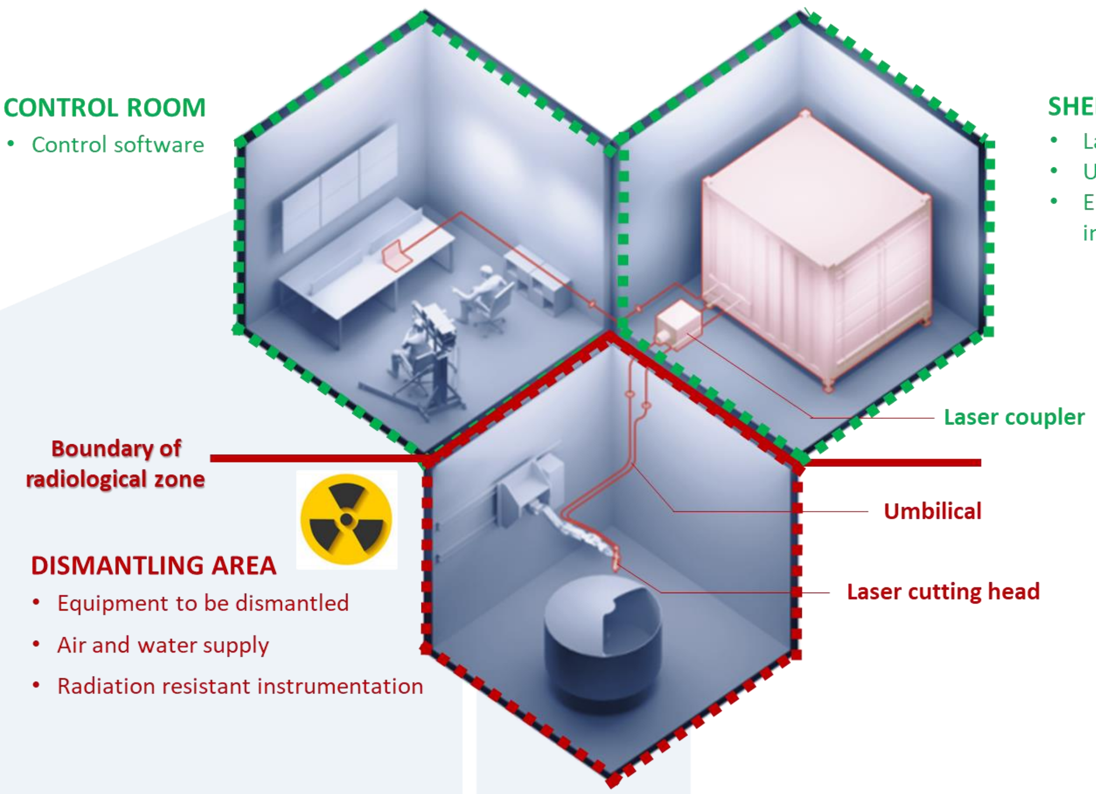

Figure 3: The three main areas and the associated equipment for the laser cutting system.

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

From the control room to the laser source, there are no significant distance constraints other than the length of the cables linking the two. However, 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, each of the three main areas are described further.

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. May 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 includes 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 has the following limitations:

- **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** – In air, steel and stainless steel of thicknesses up to 200 mm can be cut with 14 kW laser power, see Table 2.

Table 2: Maximum material thickness for in-air and underwater 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
Underwater	**Stainless Steel**	40	Not tested	70	Not tested	Not tested

7.2. Comparison of In-air and Underwater Laser Cutting

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

1. The in-air laser cutting head has high tolerance (a few cm) for the cutting process, compared with underwater cutting, where the tolerance only is a few mm.
2. Underwater cutting has the advantage of water acting as a radiation shield, compared with in-air cutting.
3. The underwater laser cutting head may be used at up to 5.6 m of water depth. A minimum of 3 m depth is recommended for radiation shielding.
4. Safety risks are generally lower underwater than in air.

5. In air, risks are higher in terms of potential for damaging surrounding structures (from residual laser power), as well as releases of aerosols.

6. For underwater cutting, the water needs to be filtered, either using an existing water treatment system or by a new, dedicated water filtration system.

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. 2]. 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 100kVA).
- 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 may be supported by supplementary clean-up systems.
- Ventilation (filtered that includes capabilities for capturing aerosols).
- Radiation protection (including area radiation monitoring in the reactor building and process radiation monitoring (i.e., ventilation, water).
- 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 need to specify all interfaces with their respective facility and ensure compatibility between the existing systems of its facility with 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. Regarding the ventilation, the interface shall be such that the laser system will stop automatically upon loss of ventilation, supported with alarms for manual stop, if needed.
3. Users must also ensure that their off-site emergency plan will not require any modifications due to the installation and operation of the laser cutting system. Otherwise, users should 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 need to be checked and confirmed that they conform to the requirements of the laser cutting system.
5. Security aspects, including cyber security, also need to 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 techniques. 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. Working 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 include:

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 should include but not be limited to:

    - General laser safety training.

    - Use of the laser cutting system (including use of the manipulator).

    - Procedures if malfunctions are encountered, including loss of ventilation, loss of power, etc.

3. All staff with access to the dismantling area should be aware of the general laser risks.

4. The trainer should 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 guidance on specific components of the laser cutting system, also see Section 5):

1. Guidance from the respective manufacturer of the different components must be followed during installation of the laser cutting system.
2. Personal protective equipment should be used in accordance with the facility's requirements in the associated work area.
3. The robotic arm should 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 is needed to lift the shelters into position. When performing these lifts, it is recommended to avoid high winds or other poor weather conditions, 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. A specific circuit breaker for electrical protection of the laser source may be needed to meet the requirements of the manufacturer.
8. 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" should be provided on the laser fibre, in accordance with the manufacturer's instructions.
9. 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.
10. For underwater cutting, the umbilical should be pressure tested as part of installation.
11. To protect the cavity liner in case of heavy load drop or any residual power issues, a protective cover should be installed on the floor of the cavity.

12. For underwater cutting, water treatment of the pool water that includes filtration of dust, metal chips and other particles needs to be installed (to reduce contamination levels in the water and ensure good visibility). Alternatively, an existing water treatment system may be used if it has sufficient capacity. The water treatment system should be located as close as possible to the cutting area.

13. Installation of localized ventilation is recommended to reduce the spread of contamination (preferably a local ventilation system with pre-filtration, to reduce risk of the high-efficiency particulate air (HEPA) filter becoming clogged).

14. 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 parameters of the laser cutting system need to be determined before every cut to minimize the risk of residual power scenarios (see Section 8.3) and ensure that the cutting process is robust. The operation parameters are determined by the thickness and nature of the piece that will be cut, while taking into account the structures behind it. The operation parameters include:
   - Power.
   - Distance between the nozzle and the piece to be cut (the "stand-off").
   - Cutting speed (which should be the fastest speed possible, to reduce risk of residual power impacting background structures, without reducing the robustness of the cutting process).
   - Angle.
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 from the cutting to fall onto the equipment and cause damage outside the cutting area.
4. The distance between the laser cutting head and the piece that is being cut typically must be between 10 and 50 mm (for in-air cuts care needs to be taken to ensure that the cutting head has access and is not blocked on its trajectory during the cut; if needed, parts that are in the way need to be removed).

5. If the system is to be moved, the water in the cooling circuit should first be purged of water.
6. 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 (i.e., risk of loss of structural integrity, load drops, etc.)
7. 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.
8. 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 laser parameters have been set.
9. The absence of any combustible materials in the laser beam's direction should be confirmed, to avoid risk of accidental ignition.
10. Preparations need to include ensuring that the equipment can be positioned within the distance range throughout the trajectory of the cut (that is, that the manipulator and cutting head have room to move, without any other items being in their way).
11. 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 to the rear side of the piece, i.e., forming attached slag.

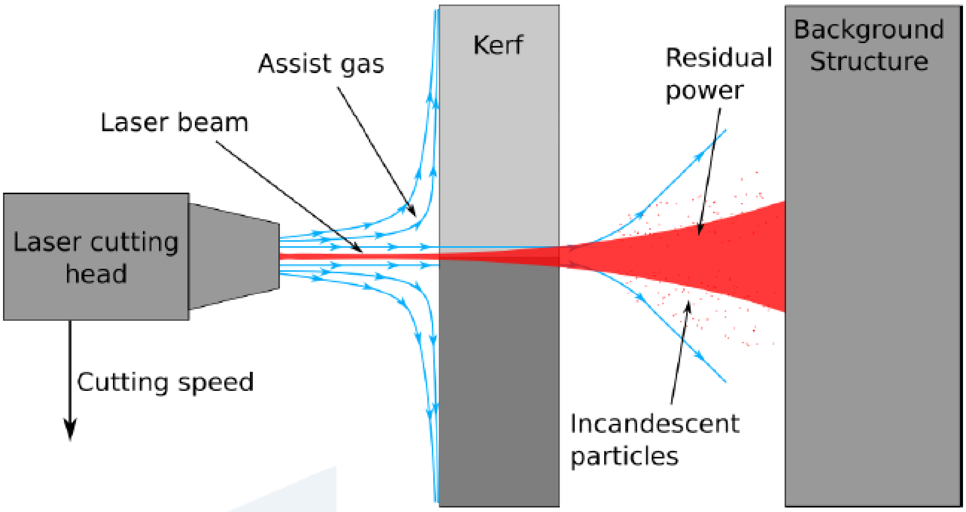

Figure 4: Laser cutting through a piece, creating a kerf and the release of incandescent particles.

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:

- If cables are accidentally cut by the laser.
- If rupture is discovered on the laser fibre (by electrical sensors in the fibre).
- If moving for too long while the laser is still active, to avoid risk of damaging other structures.
- If differential pressure in the ventilation filters is lost.
- If temperature is too high in the laser cutting head (as it risks damaging the optical lenses).
- If abnormal sensor indications occur (such as temperature or pressure changes).
- If fire or smoke is detected.
- If radiation monitors detect elevated dose rates or contamination levels outside of the confinement area.

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

1. Guidance from the respective manufacturer of the different components must be followed during operation of the laser cutting system.
2. During cutting, the control room should be staffed with a minimum of two persons (an operator and a supervisor) to enable verifications during operation.
3. While the laser is in use, no persons are allowed in the areas that risk being pointed at by the laser beam.
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 should 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 should be automatically cut in the event of loss of ventilation or loss of water filtration.
9. The system should be equipped with a programmed stop mechanism so that the laser automatically stops if the manipulator stops moving for too long while the laser is still active (to avoid risk of piercing the material behind the cut pieces).
10. The emergency stop of the laser should be designed such that it does not shut off the power to the laser source – but just the transmission to the laser cutting head.
11. To ensure that the amount of power delivered by the laser source and the laser cutting head is accurate, regular checks should be performed (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 should 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 absorbed 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 includes:

1. The cut should be planned so that the risk of residual power causing damage to background structures is minimized, by aiming to ensure that there is a sufficient distance between the cut piece and the background structure.
2. The cut may be preferrable to test in a mock-up before laser cutting in the dismantling environment.

8.4. Release of Aerosols, Dust, Fumes and Particles

To avoid the spread of aerosols, dust, fumes and particles that are released from the cut pieces during laser cutting, 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. 2].

During in-air cutting, the laser cutting system can include a local collection system adjacent to the laser cutting head. 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 are scrubbed. The efficiency of the scrubbing is a function of the water depth. However, 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 (to reduce contamination levels and ensure visibility).

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. 2].

8.5. Hydrogen Gas Generation

During underwater laser cutting of metallic materials, it is important 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 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. Based on the *Generic Safety Assessment* [Ref. 2], installation of a hydrogen gas sensor on the exhaust line is not needed; however, it may still be considered as an additional safety measure to enable monitoring of hydrogen gas generation.

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 production must be performed and associated 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. If the air bubbles cause visibility issues:

1. The laser cutting may be paused to allow air 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. 2].

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 must be removed and 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 needs to be replaced (since the optics inside cannot be cleaned).
4. Support systems (such as ventilation and water purification) need to 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 in other reactors.

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 techniques. The main types of radioactive waste that arise as a result of laser cutting include:

1. The pieces resulting from the laser cutting.
2. Particles, debris and, if applicable, metal pearls (formed during underwater cutting) fallen to the floor.
3. The laser cutting head and umbilical (see Section 9.1).
4. Air filters and water filters/ion exchange resins, as applicable.
5. Any 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 techniques.

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.

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 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.