FIBRE DELIVERED LASER BEAMS – AN ALTERNATIVE COST EFFECTIVE DECOMMISSIONING TECHNOLOGY

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Abstract

Decommissioning of a nuclear power plant is the systematic deconstruction of a contaminated, complex facility, which can be made up of large metallic components including the reactor vessel, steam generators, pumps, tanks and supporting systems, which often include many meters of tube networks. Remotely operated techniques and processes to cut waste material into smaller pieces are required that develop new and novel approaches that facilitate a smarter decommissioning process, ie one that is safer, faster and cheaper. Amongst the available thermal cutting processes for metallic components, multi-kilowatt, fibre delivered laser beams are well suited to remote deployment, due to the lack of reaction force, light and compact process heads and limited fume generation. Such lasers potentially offer increased cutting speed, high levels of automation, ease of deployment, flexibility of use and as a result, can be used to reduce volumes of radioactive waste through more selective cutting, thus reducing both costs and radiological risks. In addition, such lasers can be placed in an uncontaminated area making them reusable for many cutting tasks, as well as for decontamination of metallic and concrete surfaces, which most other cutting techniques are not able to perform. This potentially makes the laser an alternative, cost effective decommissioning technology. In this paper, the capability of a 5kW multi-mode laser is presented for cutting of unstructured tube networks in hazardous and confined nuclear environments. In addition, cutting results on thick plate material, representative of that which might be found in pressure vessels and dissolvers, are presented. In addition highlights of industrially relevant demonstrations are also mentioned.

Keywords: Decommissioning, Laser, Remote-Cutting, Dismantling

1 Introduction

As of 2012, 138 civil nuclear power plants had been shut down in 19 countries, including 28 in the United States, 27 in the United Kingdom, 27 in Germany, 12 in France, 9 in Japan and 5 in the Russian Federation [1]. Only 17 of these power plants have been decommisioned so far. Decommissioning of a nuclear facility is a complex process that takes years. The cost of decommissioning nuclear power plants vary greatly, depending on the plant type and size, its location, the proximity and availability of waste disposal facilities, the intended future use of the site, and the condition of the plant and the site at the time of decommisioning. Each decommissioning task can be very different to the next, so an innovative and flexible approach to process deployment may be necessary.

In the United States, the estimated average cost of decommissioning a nuclear power plant is around US$500 million or approaximately 10-15% of the initial capital cost. In France, the estimated cost of decommissioning a power plant rose by 26% to €500 million, between 2001 and 2008 and it is likely to increase further [2]. In the United Kingdom, the Government's financial provision for decommissioning rose from an estimated £2 million in 1970 to £67.5 billion by 2013 [3]. It is clear that decommissioning can sometimes be much more expensive than originally budgeted [4].

Decommissioning is not simply demolition. It is the systematic deconstruction of contaminated, complex nuclear facilities, with many large components such as the reactor vessel, steam generator, heat exchangers, pumps, tanks and supporting systems, including thousands of meters of pipes – along with even greater volumes of construction materials. Although 99% of the radioactivity is associated with the fuel and the reactor vessel, which is removed following permanent shutdown and requires special attention, significantly large infrastructures remain. Deconstruction of these medium to low level wastes requires considerable time and funding, detailed planning and precise execution. It also requires a similar degree of expertise and regulatory control. A critical aspect of decommissioning is that dismantling needs to be carried out in such a way that radioactive and non-radioactive materials are seperated. This minimises the amount of waste that will require specialised handling and treatment. Controlled and selective seperation also maximises that amount of metallic materials that can be recycled, as well as the amount of concrete rubble that can be reused on site.

A key to reducing the volume of contaminated waste is to improve the seperation of material during decommissioning. But reconciling this practice with the minimisation of exposure to workers may be defiicult. In many cases remotely operated vehicles, manipulator arms and robots can be used to cut waste materials into smaller pieces. Further developement of such technologies is invaluable, as they can reduce waste volumes and increase the packing density of radioactive material to be disposed off through more selctive cutting, thus reducing both costs and radiological risks. Future decommissioning of nuclear facilities will make increasing use of non-contact remote cutting techniques, expertise, resources and waste disposal and management facilities. There is a large variety of size reduction/dismantling techniques that use cutting and are currently in use and considered state-of-the-art. They can be grouped into, A)mechanical (sawing, shearing, milling, diamond wire sawing, etc). B) thermal (oxy-fuel, thermic-lance, plasma-arc, laser beam, etc), and C) hydraulic (water jet and abrasive water jet, shears) [5-9]. Some of these techniques are also applicable underwater.

When applied underwater, generally radiation protection is improved, but visibility in the cutting area is reduced [10].

The particle size distribution of the resulting aerosol, dust and the quantity of swarf and dross that can be collected during cutting, depend on various factors: cutting technology, cutting parameters, measurment point, aeration, kind of material, and environmental conditions [11-12]. In view of the wide range of decommissioning tasks, many different cutting techniques have been developed so far to demonstrate their potential use. In one form or another all these techniques, have been used in active environment. The characteristics of some main cutting techniques that has the potential to be used in dismantling applications are highlighted in Table 1.

Table 1. *Characterirstics of some main cutting techniques.*

Technique	Oxy-fuel	Lance	Plasma	Laser	Water-Jet	Mechanical
Applicability	Low Carbon Alloy steel only	All materials	Only electrical conductive materials	Most materials	Most materials	All materials
Max. Cutting thickness	> 2000mm	2000mm	170mm	110mm	150mm	> 2000mm
Secondary Emission	Hot oxide, fumes, aerosols	Gaseous, dust and solid products	Gaseous, dust and solid products	Gaseous, dust and solid products	Abrasive, fluid product and dust	Scraps, burrs, dust
Underwater Cutting	Yes (poor performance)	Yes (dry activation required)	Yes	Yes	Yes	Yes
Contact force	Negligible	Low	Negligible	Negligible	Medium	High
Standoff tollerance	Low	Low	Low	High	Low	None
System Cost	Low	Low	Medium	Medium-High	High	Medium - High
Remote Operation	Yes	Difficult	Yes	Yes	Yes	Yes
Specific Hazard	Preheat flame and hot oxides	High gaseous byproducts and fumes	Electrical, brightness, gas and fumes	Laser beam, and fumes	Secondary treatment of Effluent	Noise and Vibration
Observation	The oxygen flow is critical	Difficult in remote operation and secondary emmission management	Need high purity gas and can only cut seleced material and geometeries	Flexible, high automation, excellent selective size reduction capability	Costly post clean up operation	Need high electrical power supply

Each cutting technique has its advantages and disadvantages. However, at present contractors mostly use mechanical techniques, because they have abundant knowldge and experience in using these tools. Neverlesess, as complexity, urgency and the cost of dealing with ever increasing challenges of decommissioning increases, organisations responsible for decommissioning operations are looking for more innovative techniques to deal with the problem. What is needed is a highly automated remote technology that can: deliver a non contact smarter dismantling process, cut most materials, cut complicated structural geometries, produce minimum secondary emmissions, deliver high throughput at large operating distances, requires minimum deployment effort and maintanance and be flexible enough to be reused in many decommissioning processes.

Laser cutting is one such technology that meets the majority of these decommissioning requirements. In the past, various high power lasers have been used to demonstrate cutting of thick-section metallic materials for nuclear decommissioning applications, where constant power density and nozzle standoff distance to the substrate were usually maintained. These included CO_2, CO, COIL and Nd:YAG lasers [13]. These lasers can also be used in other decommissioning applications such as surface cleaning and concrete scabbling [14]. All lasers offer unique capabilities, but the flexibility offered from solid-state lasers, employing optical fibre delivery of the laser power, reduces complexity and risks. Development of high power disc and fibre lasers, coupled with improvement in beam delivery, thermal management of the system and multiple channel output, have further enhanced decommissioning capability by providing scalable power in the multi-kilowatt regime with higher beam quality [15]. Furthermore, the high value asset, which is the laser itself, can be situated and maintained in a safe clean area, some 100s of meters away from the active area, thus allowing the system to be reused for several other decommissioning applications. However, the laser technology has not mutured enough to cut extremely thick materials effectively, such as reactor vessel, which requires special consideration. Nevertheless, current laser technology is well capable of cutting material in exccess of 50 to 60mm in thickness. Significant parts of nuclear facilities comprise of pressure vessels and dissolvers, with wall thickness below the 50mm thickness range and tubes with wall thickness of 10mm or less and average diameters of 60mm. It is when used to dismantle such usually medium to low level wastes, that laser technology is likely be the most cost effective cutting technique.

In the cutting of tubes, the biggest challenge encountered for decommissioning, arises due to the profile of the tubes/pipes and their juxtaposition, with respect to each other [16]. They could be bundled, multi-layered, or concentric, in various orientations and sizes. From the deployment consideration, any cutting technique employed will have to face the senario cutting around the tube becomes almost impossible. Therefore, a method of single sided tube cutting needs to be developed. Unlike conventional laser cutting of flat plates or orbital laser cutting of tubes, where the beam focus and the nozzle standoff distance is maintained constant with respect to the tube surface [17], in the single-sided laser cutting described here, both the laser focus beam diameter and the standoff distance vary relative to the tube surface in one plane. Schematics of the process set up and the laser cutting head used in the tube cutting trials are shown in Figure 1.

Since 2009 [14], TWI Ltd have demonstrated the applicability, flexibility and enhanced process performance of using high brightness fibre delivered laser beam in decommissioning applications. In this paper the potential of using fibre delivered laser technology in decommissioning tasks is highlighted, with emphasis on achieving material separation, particularly for stainless steel tubes, using single and double-sided cutting techniques developed in house.

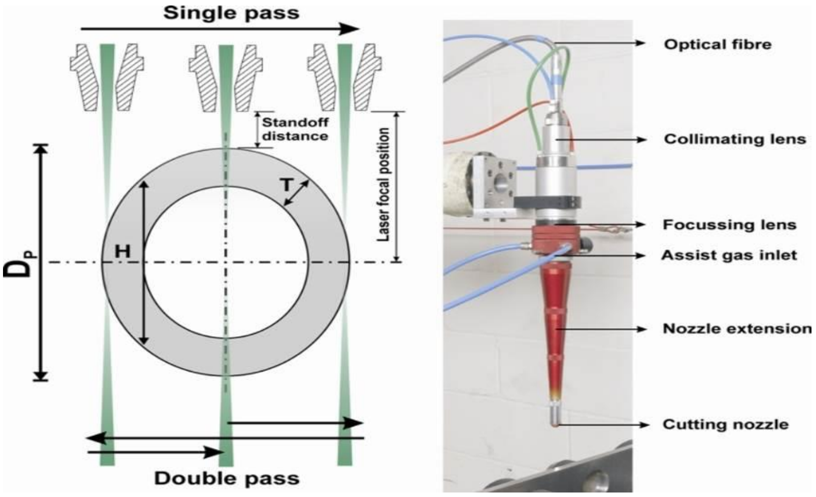


Figure 1. *Process schematics and complete cutting head assembly.*

2 Methodology

Single-sided laser cutting trials on 316L stainless steel tubes were performed using a 5kW multi-mode (MM) fibre laser with a beam parameter product (BPP) of 6mm.mrad. The beam from the laser was focused to approximately 420μm, by using collimating and focusing optics, coaxially aligned with a tailored lens system and a cutting nozzle assembly designed to operate at pressure of 8bar. Table 2 provides details of the equipment and parameters used to perform the laser cutting operations.

Table 2. *Equipment and parameters used in single-sided laser tube cutting trials.*

Laser, Power and Wavelength	4.8kW max. (BPP ~ 6), λ = 1070 – 180nm
Fibre Core diameter	0.15 mm
Collimator focal length	120 mm
Optical focal length	500 mm
Tube diameters	60, 155 & 170 mm
Tube wall thickness	1.5 to 11.1 mm
Gas presure (compressed air)	2 to 8bar
Nozzle diameter	3.25mm
Max. Cutting speeds	10 to 2000 mm/min

Laser cutting trials for a given laser power, gas pressure and cutting speed, were performed by traversing the laser beam across the tube in a straight line, while maintaining the focal position along the centre of all tubes. Laser cutting on tubes with different diameters was achieved by extending or reducing the nozzle position, but always keeping a minimum standoff distance (Figure 1) of 10mm and focal position in the centre.

Single and double pass cutting techniques were examined. Maximum cutting speeds reported here were for a complete severing of the tube. Most of the time, if there was any lack of separation, it was encountered at the sides of the tube. At these positions not only the standoff distance, but also the material thickness is at a maximum. Table 3 shows calculated maximum material thicknesses for particular tube and wall thickness combinations. In addition to laser cutting of tubes, several other metallic support structures that might be found inside a contaminated nuclear plant, were also cut with the same equipment.

Table 3. *Estimated Max. material thickness for various tube diameters and wall thickness.*

Tube diameter, D_p (mm)	Tube wall thickness, T (mm)	Max. cut thickness, H (mm)
60	1.5	18.73
60	4	30
60	5.44	34.5
60	8.71	42.3
60	11.1	46.3
155	1.5	30.4
170	7	67.6

3 Results and Discussion

Tube cutting

It is clearly desirable to cut large diameter steel tubes with just a single pass of the laser beam while traversing in one plane. Several cutting techniques were addressed and it was found that even with the maximum laser power availabe, for a single pass technique, the maximum cutting speed was very slow and complete separation of the tube was limited to tube diameters of the order 60mm and wall thickness of 1.5mm. A double pass technique produced the best results, enabling higher cutting speeds and cleaner cut surfaces. The double pass cutting was initiated and terminated at the centre of the tube, as shown in Figure 1. In one series of experiments, samples were produced with a constant laser power, for each particular tube diameter and wall thickness, by varying cutting speed, standoff distance and gas pressure, to determine the maximum cutting speed for separation. It should be pointed out that for decommissioning purposes, cut quality is not importand as long as the component ends up in two pieces. Figure 2 shows the maximum cutting speed achieved for a 155mm diameter tube with a 1.5mm wall thickness, at various nozzle gas pressures and laser power settings. The focal position of the laser beam was fixed, as shown in Figure 1. The standoff distance between the nozzle exit and the closest approach to the tube was maintained at 10mm. Pressure dependent laser cutting trials were performed with a constant laser power of 4.8kW and laser power dependent cutting trials were performed at a constant gas pressure of 8bar.

It can be seen that the maximum cutting speed is proportional to both the laser power and the gas pressure. However, there appears to be a higher dependency on the laser power. This is to be expected due to the significant variation in the available laser power density at the top and the bottom edges of a large diameter tube and it is the lower edge of the tube which is more susceptible to adhering dross for variations in both the laser power density and the gas pressure. The maximum cutting speed was attained with higher laser power, for the same gas pressure. Similarly, the cut quality, in terms of speed, was also better with higher gas pressure, for the same laser power.

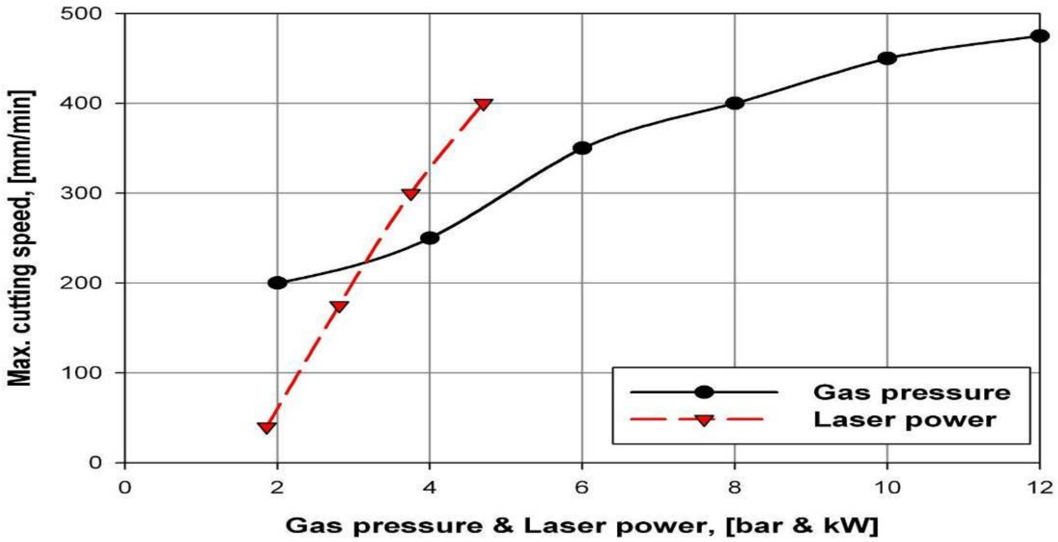


Figure 2. *Laser cutting characteristics of a 155mm diameter tube with 1.5mm wall thickness. Double pass cutting.*

Trials on 60mm diameter tubes of various wall thicknesses, with a constant laser power of 4.8kW were also carried out, to determine the effect of assist gas pressure. As for the 155mm diameter tube, the focal position of the laser beam was fixed as shown in Figure 1, using a different nozzle extension tube and the standoff distance was again maintained at 10mm. The maximum cutting speed obtained for each wall thickness is shown in Figure 3.

As would be expected, the smaller the tube wall thickness, the faster the cutting speed, This reduces exponentially with an increase in the tube wall thickness. In all cases, it was noticed that the edge quality in the lower half of all tubes cut was always poorer than in the upper section and also became progressively worse with an increase in the tube wall thickness.

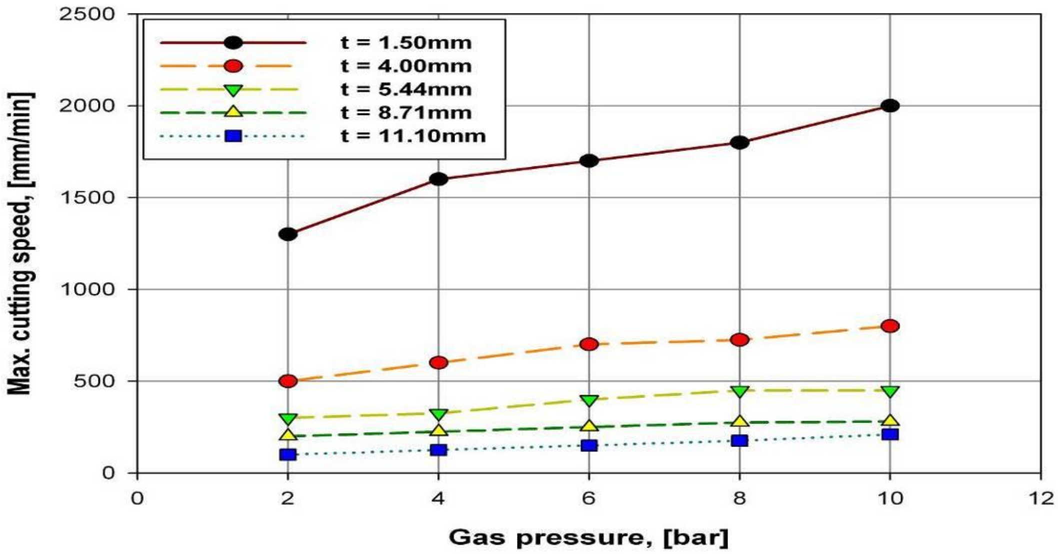


Figure 3. *Maximum cutting speeds for a 60mm diameter tube with various wall thicknesses. Double pass cutting.*

Selective Dismantling

Single-sided laser tube cutting methods were also developed for selectively removing sections of much larger tubes, and a demonstration was also made to simulate the effectiveness of remote deployment of this technology, by sectioning various pipes of different sizes, wall thickness and orientations, in one continuous robot program. Figure 4 shows the largest diameter tube, at 170mm, with a wall thickness of 7mm, used in this work. This was cut with a laser power of 4.8kW, at a linear speed of 100mm/min and using 8bar of compressed air assist gas. In this case a three pass technique was used; the first two cuts removed a segment from the front of the tube, thereby providing more energy at the rear of the tube during the third pass, which produced complete separation. A total cutting time of 7min was required for this tube.

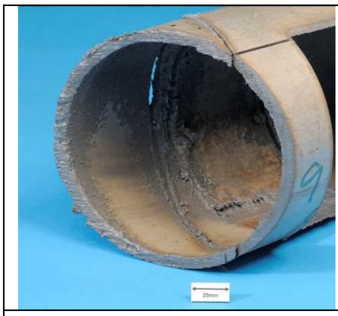
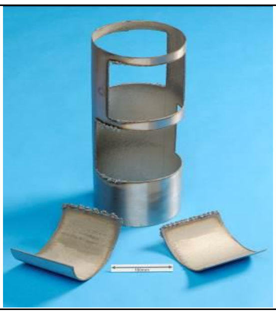
		
Segmentation of 170mm diameter tube with wall thicknes of 7mm	Selective dismantling of 155mm diameter tube	Angle seperation of 155mm diameter tube

Figure 4. *Different cutting strategies allowing removal of sections and cutting at angles not perpendicular to the tube axis.*

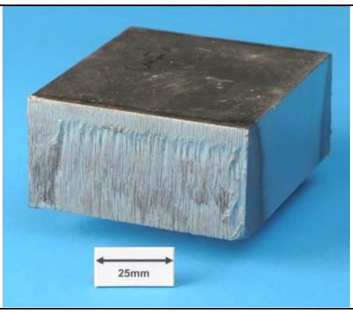
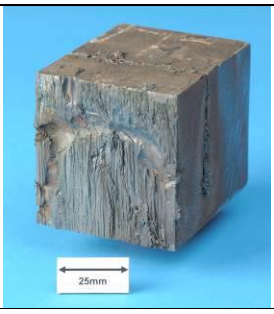
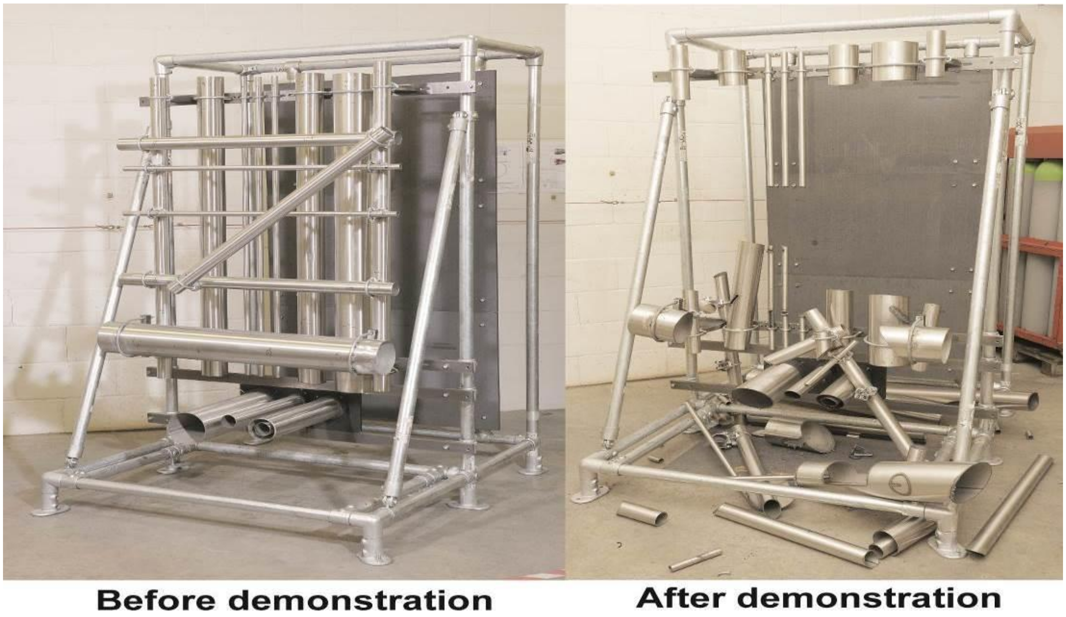
		
Selective dismantling of 600mm diameter pipe with wall thickness of 25mm	Selective dismantling of 200x200mm I-beam with wall thickness of 10 and 12mm	seperation of 50x50mm T-beam with wall thickness of 12mm
		
Seperation of a 87mm thick structrual concrete slab	Seperation of a 40mm thick S355 C-Mn steel	Seperation of a 60mm thick S355 C-Mn steel

Figure 5. *Demonstration of the capability of laser cutting for decommissioning applications relevant to commonly used industrial structural components.*

Sections of tube can be removed easily (should access into the interior be required) and tubes can be cut with the beam incident (at least), up to 45 degrees to the tube axis. Indeed, using the current equipment, it is also possible to cut arrangements of concentric tubes and tube bundles. Selective laser dismantling techniques were also applied to several other materials which might be found during decommissioning of a nuclear power plant. Structures representative of large pressure vessels, I, L and T-beams for surpport structures, thick plates and and concrete slabs, have been laser cut. Figure 5 shows these selectively laser cut samples.

Tube cutting demonstration

Tube networks or “the nuclear jungle” as it is described in nuclear circles, have collections of tubes of various sizes, thicknesses and orientations. In order to simulate conditions inside a contaminated cell, a collection of tubes of various diameters and orientations were mounted on a support framework. The support framework was designed to be re-used after each demonstration. The back wall of the support structure was constructed from graphite sheets, used to absorb any laser beam propagating past the tubes. Tubes of diameters from 25mm to 155mm, including arrangements of concentric tubes, were fixed to the support frame using the type of fixtures commonly employed in practice. Using a laser power of 4.8kW and an assist gas pressure of 8 bar, all tubes were cut (using the same nozzle assembly) with a single robot program. Over 50 cuts were made on the tubes and the fixtures, to dismantle this tube network in an elapsed time of 15min. Figure 6 shows before and after images of the demonstration exercise.



Before demonstration

After demonstration

Figure 6. *Tube cutting demonstrator, before and after.*

“LaserSnake“ demonstration

A second, “LaserSnake“ demonstration, highlighted the ability of a snake arm robot armed with a fibre laser cutting tool to maneuver through confined spaces and selectively laser cut components inside a simulated contaminated nuclear cell. A mock-up cell (2.5m x 2.2m x 1.5m) containing a 1m long access aperture (200mm in diameter), a pressure vessel wall (6mm thick) and a subsequent arrangement of pipework, was constructed. Figure 7 shows the system entering the cell through an access aperture, avoiding an obstacle and then cutting a access hole in the wall of the pressure vessel. The LaserSnake then enters the pressure vessel to inspect the pipework and selects, using its on-board vision system, the targets that require cutting, before re-tracing its movements to finally withdraw itself from the cell.

Figure 7. *LaserSnake demonstration.*

Laser Scabbling demonstration

The same laser with a change in the optical configuration and using a new processing head, can also be used for selectively removing the surface of contaminated concrete. The process was found to be independent of the attitude of the concrete. Figure 8 is a still image taken from a video sequence showing the system operational in the removal of a 1m x1m square section of concrete, to a minimum depth of 10mm, using a single pass. Note the effectiveness of the debris removal system. Also seen in this image are laser stripes used to measure the concrete surface topography, making the system fully automated.

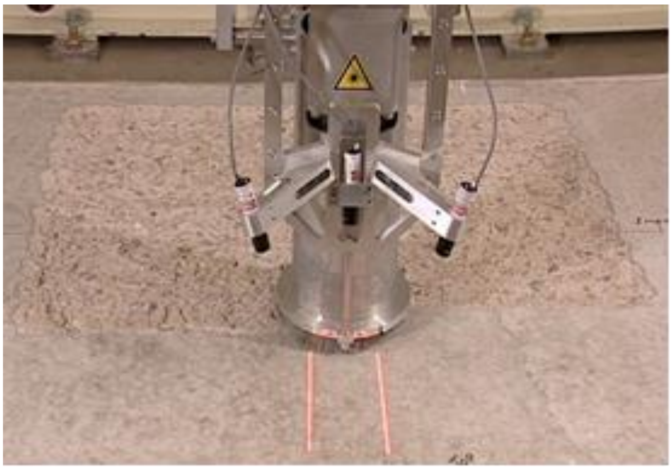


Figure 8. *Laser scabbling demonstration* selectively removing *a 1 x 1m section of concrete in single pass*

4 Cost effectiveness of using fibre delivered laser technology in decommissioning

Cost effectiveness of using fibre delivered laser technology for decommissioning can be demonstrated in the following areas:

- The capability of a single laser cutting system to cut most materials of many geometrical configurations means reduced equipment deployment and maintenance inside a contaminated cell. This should reduce the decommissioning time and radiological risks to workers.
- The laser cut kerf is narrower when compared with other thermal cutting techniques, allowing faster cutting speed and release of smaller volume fumes and dross in the nuclear cell and ventilation systems. This should reduce post processing cost, reduce filtration change and maintenance, and reduce radiological risks to workers.
- Light processing heads, with minimum services inside the contaminated cell provide the opportunity for much smaller and simpler manipulation systems to be used for deployment. This reduces efforts in deploying the system and the overall cost of the system needed inside the cell.
- The most expensive part of the decommissioning system with respect to fibre delivered laser technology is the laser itself, and these are becoming less expensive, They can be located in a clean uncontaminated area and the same system therefore has the potential to be used for many applications. The only disposable parts will be the cutting head and the delivery fibre, which are, compared to the laser, cheap and easily replaced.
- Laser cutting has proven itself to be the most efficient and effective metal cutting technology in the Job-Shop environment. A dedicated decommissioning “Chop-Shop“ can be an effective solution to improve waste packing density, requiring less storage and special construction of storage boxes, thus providing better waste management strategy.

5 Conclusions

A very effective and efficient system for dismantling nuclear grade stainless steel tubes and steel structures, using fibre delivered laser technology has been developed. The cutting head, tailored for these applications, is light, has a significant standoff tolerance, and is relatively simple to deploy and operate remotely. For tube cutting from one side, for tubes of different diameters and wall thicknesses, the most critical regions are the tube sides, which require both higher laser power and assist gas pressure, for clean separation. As a result, a double pass technique was preferred to a single pass method as the optimum laser cutting configuration.

Laser technology has also demonstrated itself to be a sophisticated system for concrete scabbling, compared with other decommissioning technologies; this makes laser, a very versatile technology. The selective demonstrations shown the processing speeds and flexibility offered by fibre delivered laser beams, to be an effective tool for decommissioning in confined spaces. These qualities associated with fibre delivered laser beams can reduce complexity during the deployment process, provide minimum process interruptions, and improve waste management strategy, which all can result in improved safety, thus reducing decommissioning costs.

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