6.3.1.4. Orbital cutters

Orbital cutters can be manually actuated devices or self-propelled units that cut as they move around the outside or inside circumference of a pipe or vessel and they are an effective means of segmenting pipes and circular vessels (Fig. 21). Three different types of tool are used for orbital cutting:

- *Swaging cutter.* This uses a hardened wheel which compresses and shears the metal. This technique is able to cut thin walled metal pipes [437, 438].
- *Lathe tool.* Typically two lathe tools are placed diametrically opposite one another and rotate around the pipe to be cut; a ratchet system feeds the tool into the metal after each rotation, thus performing a cutting operation similar to that of a lathe. Such a tool can be used on small pipes [439] as well as on large cylindrical vessels [150]. The tool can be arranged to rotate either outside the pipe, as at the Hanford C reactor [440], or inside as at JPDR [132, 441–443].
- *Milling tool.* In place of the hardened wheels on the rotating head, a small milling cutter (e.g. slit cutter) is used to cut a slit in the pipe while rotating around or inside it. The tool can be fed by a ratchet after each rotation of the head, or fed continuously by a dedicated system. Such a tool has been used at Germany's Mehrzweckforschungsreaktor [444].

Orbital cutters can be controlled remotely, allowing the operators to work at a distance from the radiation area, but they often require manual positioning in the first instance [440].

6.3.1.5. Abrasive cutting wheels, blades, wires and core drills

These are electrically, hydraulically or pneumatically powered wheels, beads or chain links containing abrasive held in a semi-rigid supporting matrix. Typical abrasives used include aluminium oxide, silicon carbide or diamond and these cut the workpiece by local shearing at multiple cutting points. Abrasive cutters can be used either dry or with a coolant, such as water, which is often recirculated to reduce secondary waste volumes. The technique is used extensively worldwide, in a wide range of industries. At least 100 years of experience and development has taken place to establish this branch of cutting.

(a) Carbides and aluminium oxide

These abrasive materials are supported by a binding material in the form of a circular disc and will cut metal, brick, or concrete with reinforcing bars. Deployment systems for most applications are commercially available and are well developed.

FIG. 22. Dry cutting of cast iron shielding blocks using diamond tipped blade saw.

Examples of where such tools have been used are given in Refs [293, 371, 428, 445, 446]. General comparisons between grinding discs and other cutting tools are provided in Refs [182, 429, 433, 434].

(b) Diamond

Diamond abrasives are embedded in the beads of diamond wire saws, in cutting wheels and coring tools, and also in the chain links of diamond chainsaws. Typical applications are shown in Figs 22–24. Diamond wire has been conventionally used for cutting through concrete (also reinforced concrete) and masonry (e.g. at the Zimmer NPP) and also used at the FSV reactor [68, 136, 447] (see also Refs [448–450]). In a different application, wire sawing was used to dismantle the stack at the National Research Experiment reactor in Canada [451]. More recently it has also been developed for cutting through heavily reinforced concrete and pure metal structures and for cutting without the use of liquid coolant [183, 197, 449, 452, 453]. R&D activities in Japan are described in Refs [454, 455]. Diamond wire saws have also been used in Germany at KKN [456] and at the Grosswelzheim Heissdampfreaktor (HDR) [457].

Diamond blades or wall saws are widely used during civil construction work for cutting concrete and reinforced concrete and were used to dismantle the biological

FIG. 23. Creating new cell entrances using a diamond cable cutting machine.

FIG. 24. Concrete cutting using a diamond tipped blade saw.

shield at JPDR [25, 132, 253, 441, 443, 458–461]. These blades have now been developed for cutting without coolant and for the cutting of pure metal structures.

Diamond corers have a similar construction to that of circular diamond saw blades, except that they are cylindrical in shape. Like the circular blades, they can be used to cut concrete or steel structures with or without coolant. Corers have been used, e.g. at HDR, for concrete removal [457]. They are commonly used for drilling holes, for stitch drilling operations [25, 132, 183, 253, 441, 443, 448, 458, 459, 462], or for removing samples of material.

An emerging technology in the field of abrasive cutting is the use of diamond chainsaws. These can be used for cutting both concrete and reinforced concrete [197, 376].

6.3.1.6. Explosives

Explosive dismantling or cutting is well known and the three main types of charge employed are:

- *Conventional explosives.* These have a relatively low detonation speed, where the gas expansion and shock wave are used to reduce the workpiece size.

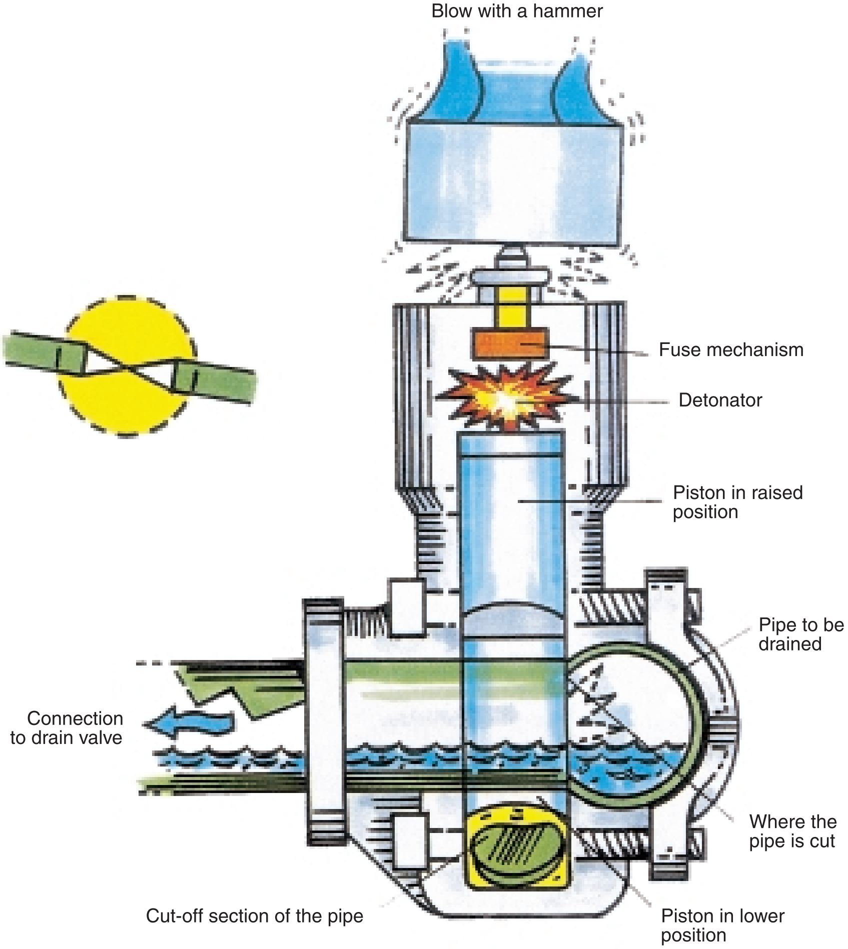

FIG. 25. Diagram illustrating the principle of an explosive drilling clamp, Kjeller reprocessing plant, Norway.

- *Shaped explosives.* These are high velocity compounds where the energy deposition and shock wave are used to fracture the workpiece at a precise point in a controlled manner.
- *Linear shaped charges.* These use the force of the detonation as the energy source to propel a metallic (usually copper) 'V' shaped 'blade' into the workpiece in order to cut it.

The use of, and references for, these different types of explosive dismantling and demolition techniques are summarized below (see also Fig. 25):

FIG. 26. Drilling being carried out for the insertion of explosives prior to the demolition of biological shield structures by controlled blasting, JPDR decommissioning project.

- *Controlled blasting:* This has been employed on the exhaust stack at SRS [185], at Fernald [18], at JPDR [253, 463, 464], at KKN [67, 197, 367], and at the LIDO reactor in the UK [181, 394, 465, 466]. Controlled blasting has also been tested on a 1:1 scale mock-up at BR3 [130, 467, 468] and an analysis made for the G2/G3 reactors in France [197, 469]. Figure 26 shows the preparation for demolition of a biological shield by controlled blasting at JPDR. A general overview of this technique is given in Refs [197, 250, 448, 449, 470].
- *Shaped explosives:* These have been used at JPDR [132, 183, 441–443, 460] to cut pipes up to 90 mm in diameter in air (Fig. 27), at the DIDO reactor in the UK to produce boreholes [197, 471] and at KKN [446]. A general overview of this technique is given in Refs [197, 448].
- *Linear shaped charges:* Linear shaped charges employing metal blades have been used at the AT-1 reprocessing facility in France [197] to dismantle tanks and have also been used at the LIDO reactor [197, 394] and at JPDR [123, 132, 441–443]. A general survey of this technique is given in Refs [197, 448].

The above techniques have been extensively used in the conventional demolition industry. However, the provision of adequate safety arguments may limit their use in the nuclear industry.

FIG. 27. Emergency condensate system pipe cut by shaped explosive, JPDR decommissioning project.

6.3.1.7. Milling

Metal milling employs a broad range of cutting tools. These include end mills, slitting wheels, face mills, etc. These milling tools were used in dismantling the reactor internals [289, 290] and thermal shield [266, 267, 287] at the BR3 reactor (Fig. 28). A special milling machine has also been developed and tested in the UK for the removal of the control blade mounting frames at the Universities research reactor [462].

An alternative strategy to recategorize RPVs into high or low level waste streams on the basis of milling was recently proposed [472]. This strategy advocates the use of a milling cutter to remove a layer from the pressure vessel wall, the reduction in wall thickness thereby lowering the active inventory of the remaining material before completion of dismantling. A general comparison of the performance of milling cutters with other dismantling techniques can be found in Refs [429, 448].

6.3.2. Thermal cutting techniques

In general, the main advantages of thermal techniques over other methods such as mechanical cutting are that:

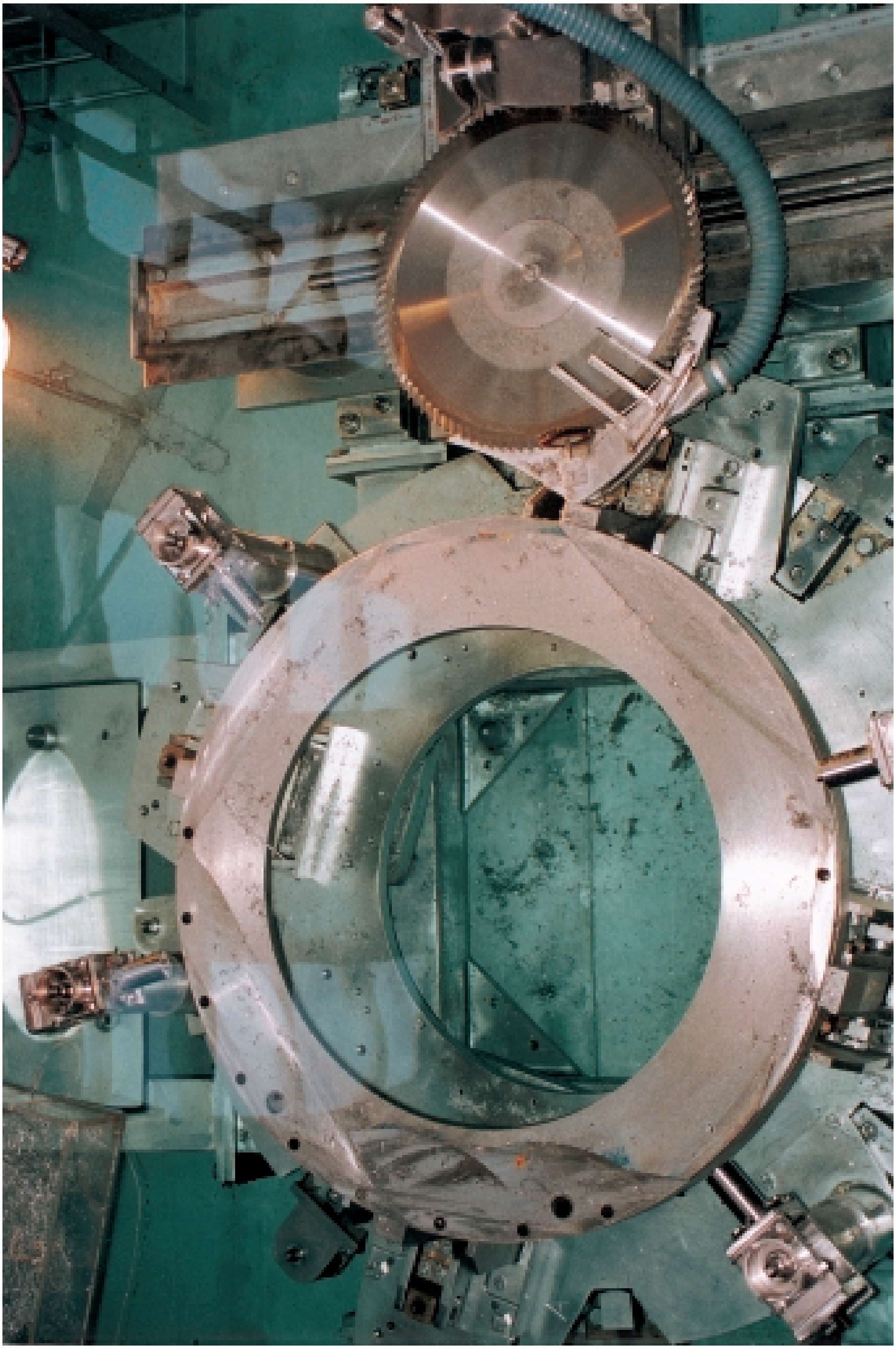

FIG. 28. Cold testing of the milling cutter at the BR3 decommissioning project.

— The cutting speeds are generally faster,
— Remote operation is often possible because the equipment is lightweight,
— The deployment system only has to accommodate small reaction forces during cutting as the tools do not require physical contact with the workpiece.

The main disadvantage is the production of aerosols, dust and dross which create issues of concern with respect to worker and environmental protection, visibility problems (mainly in underwater applications), and the production of large volumes of primary (owing to the thickness of the kerf) and secondary wastes. An additional drawback with the cutting of contaminated components which are to be decontaminated is the danger of the contamination being incorporated within the solidified slag on the cut workpiece.

For underwater cutting, it is necessary to have efficient water filtration processes to maintain water quality and to use filters working in series with decreasing holding capacity but with increasing performance in order to minimize the total waste volume. For cutting in air, it is necessary to have efficient air filtration, either locally or in the cutting containment, and to have regenerable pre-filtration processes to protect the main ventilation filters, which can be rapidly blinded by the aerosols produced.

6.3.2.1. Plasma arc cutting

Plasma arc cutting is based on the establishment of a direct current arc between a tungsten electrode and the surface of a conducting metal. The arc is created by ionizing a gas (plasma gas) and then blowing the ionized plasma towards the surface of the workpiece in order to form a conductive pathway down which the main plasma current passes (Figs 29–31). The heat generated by the impingement of the arc on the workpiece causes local melting and the force created by the velocity of the plasma gas stream blows the molten metal away from the melt pool, thereby creating the cut. Plasma cutting is a fast process and the cutting heads are lightweight, easy to use and can be deployed either manually or remotely. The process can be used both in water and in air, although control of the aerosols produced is an issue. Extensive references exist on the use of plasma arc in many decommissioning projects and these are listed below.

(a) Plasma arc in air

The plasma arc in air technique dates back to the 1930s. Developments in some of the details of the technique continue to be made although the technology can be considered to be mature. The cooling gas, which is often the same as that used to conduct the current (e.g. air), can be treated in many cases by existing ventilation

FIG. 29. Plasma cutting of metal components.

systems. The cutting rate when using gas-cooling of the electrode is lower than with water cooled systems owing to the need to reduce power density. Testing of this technique has been carried out at Fontenay-aux-Roses in France [197]. Flat metal surfaces (e.g. drip trays) have been cut using this technique at the Eurochemic plant in Belgium [136] and at JPDR [252] the storage pool lining has been sectioned, and metal piercing has been carried out at Elk River in USA [183]. Elsewhere, internal semi-remote cutting of small bore pipework and reactor standpipes has been successfully carried out at the WAGR [80, 129, 473, 474] and steam generator channel heads and tube sheets have been cut at the Ågesta reactor in Sweden [299]. Pipes and tanks have also been cut at the Rapsodie reactor [256] and remote air plasma cutting has been used to cut testing machines and maintenance equipment at the material monitoring facility (PNC) in Japan [346]. Other references to be consulted include Refs [77, 182, 305, 371, 433, 434, 445, 446, 448, 475, 476].

(b) Underwater plasma arc

Underwater plasma arc technology is well developed and used in many industries where high cutting rates are required. However, tests at the Pegase reactor in France revealed a loss in efficiency in cutting stainless steel sheet, 100 mm thick, below 2 m of water [477]. Reactor internals and other thick sections at JPDR have

FIG. 30. Plasma arc cutting being used during the removal of the equipment employed for decanning uranium elements, Kjeller reprocessing plant, Norway.

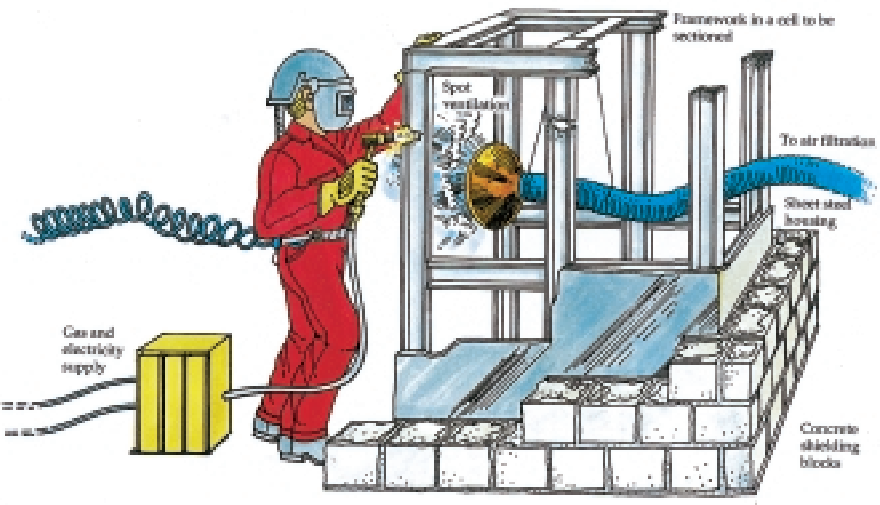

FIG. 31. Diagram illustrating the principle of a plasma arc cutting operation.

also been cut using this technique [25, 132, 441, 460, 478–480]. At the EBWR, size reduction of the reactor internals has been performed [423] and at the BR3 facility, segmentation of thermal shield rings was carried out, after in situ cutting by other techniques such as electrodischarge machining (EDM) and mechanical sawing [130, 266, 289, 290, 292]. The underwater cutting of plutonium contaminated materials has also been proven at Three Mile Island reactor in the USA [481]. Other references to be consulted include Refs [68, 183, 184, 267, 283, 287, 291, 376, 377, 426, 429, 434, 447, 482, 483].

6.3.2.2. Flame cutting

Flame cutting is a well established and mature technology and uses a flowing mixture of a fuel gas (acetylene, hydrogen, propane) or fuel vapour (gasoline), and oxygen, which are mixed and ignited to produce a high temperature flame. In the case of carbon steels the flame is brought into contact with the surface of the workpiece, which is allowed to heat up before the cutting oxygen is injected into the centre of the flame oxidizing the workpiece. As iron oxide melts at a lower temperature than the parent metal, the oxide melts and is blown from the melt pool by the flame, thereby producing a cut. Oxyfuel gas cutting can be deployed either manually or remotely, in air or water, and it can cut a wide range of steel thicknesses. Examples of its use are reported in Refs [80, 129, 146, 197, 429, 445, 448, 476, 484].

FIG. 32. Oxygas cutting equipment in use at the Fernald facility, USA.

Thicknesses up to approximately 3 m have been cut in a laboratory trial [483, 485].

The cutting of stainless steel has been less successful using this technique owing to the high melting points of the chromium oxides produced [486]. The technique has been used to cut thin sections as reported in Refs [252, 299, 487]. Cutting is achieved as a result of the flame causing localized melting of the parent metal, the gas stream removing the molten metal from the melt pool in a continuous process.

Testing of an oxygasoline torch for the cutting of steel has been undertaken at Fernald [488, 489] (Fig. 32) and in Japan tests have been carried out using an arc gouging and flame cutting system to size reduce sections of an RPV [490, 491].

FIG. 33. Thermal cutting at HDR in Germany.

6.3.2.3. Powder injection flame cutting

Powder injection flame cutting is a variant of the standard flame cutting process reported in Section 6.3.2.2. Powder injection flame cutting involves the introduction of iron or a mixed iron/aluminium powder directly into the central oxygen jet of the fuel gas flame, causing an exothermic reaction between the excess oxygen and the powder. This increases the flame temperature and gas momentum, allowing the cutting of a variety of materials such as thick sections of stainless steel and concrete. The technique can be likened to a continuous thermic lance. Details of laboratory tests and actual operation are provided in Refs [418, 449, 492]. The process produces a considerable amount of aerosol and secondary waste [448, 492] and for this reason has not been used on German decommissioning projects. The technique is well established for non-nuclear applications and is now available to the nuclear industry.

6.3.2.4. Thermic lance (oxy arc or arc slice)

The thermic lance consists of an iron pipe packed with a combination of steel, aluminum and magnesium wires through which a flow of oxygen gas is maintained. The lance cuts are achieved by thermite reactions at the tip of the lance in which all constituents are consumed. Lances vary in length from about 0.5 m to more than 3 m

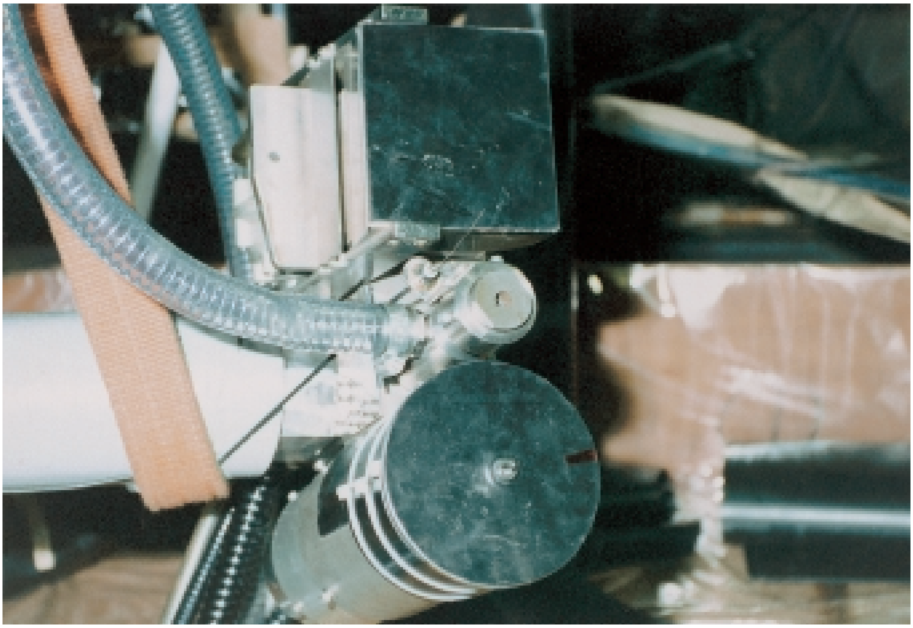

FIG. 34. Cutting nozzle of the water jet cutting system used in the demolition of biological shield structures at the JPDR decommissioning project.

and have a range of diameters. Ignition of the lance is normally performed using a flame, electric arc or battery pack.

This technique will cut a wide variety of materials and can be used for cutting slits and holes. It is not recommended for highly activated or contaminated components as it produces large amounts of aerosol and usually requires manual intervention.

This technique was used to cut the top biological shield of the WAGR [129, 445, 474, 476] and has also been used at the HDR in Germany (Fig. 33). Other details of its use are to be found in Refs [182, 183, 433, 434].

6.3.3. Abrasive water jet cutting

Abrasive water jet cutting involves the use of an abrasive, e.g. garnet sand, propelled by high pressure water. It is effective in cutting reinforced concrete and is capable of cutting virtually all materials [183]. This technique has been tested on a mock-up of the JPDR for cutting reinforced concrete [25, 132, 183, 253, 441, 443, 458, 460, 493, 494] with high cutting efficiencies being observed (Fig. 34). However, depth control proved problematic and resulted in the production of excessive quantities of sludge [464].

A study on the minimization of secondary wastes and handling of aerosols is reported in Ref. [495]. This technique has been also used at the EBWR in the test cutting of the reactor vessel [496] and at the SRS [77]. It is considered a proven method of cutting concrete [448]. Tests have been carried out in France under the EC R&D programme on decommissioning [354] and research work on this technique and its applications to industrial projects in Germany are described in Refs [352, 353, 483, 497]. A discussion of further developments and a comparison between abrasive water suspension jet and abrasive water injection jet cutting is reported in Ref. [498]. Other references are [429, 448, 449].

6.3.4. Mechanical demolition techniques

6.3.4.1. Wrecking ball or wrecking slab

A wrecking ball is a conventional demolition technique, typically used for demolishing non-reinforced or lightly reinforced concrete structures less than 1 m thick. This technique is recommended for non-radioactive structures. It was used successfully in dismantling the Elk River containment building, but was not successful at the Shippingport NPP, at the Penn Princeton accelerator (PPA) [448] and at KKN [446]. In these cases the concrete was too thick and heavily reinforced (see also Ref. [449]).

6.3.4.2. Expansive grout

Expansive grouting is a civil engineering technique which has found some use in the nuclear industry. It is used to fracture non-reinforced concrete by drilling holes and filling these with a wet grout mixture. As the grout cures it expands, creating internal stresses within the concrete substrate (see Section 6.2.2.16). It has been used during the PPA decommissioning project to separate activated concrete from non-activated/contaminated concrete blocks [423, 448] (see also Ref. [449]).

6.3.4.3. Rock splitter

Rock splitting is a technique which has been ‘borrowed’ from the quarrying industry. The rock splitter is a method of fracturing rock or concrete by hydraulically driving a wedge shaped plug between two expandable guides into a predrilled hole [183, 423, 448]. It is ideally suited for fracturing concrete in limited access areas. Hydraulic splitting devices and pneumatic hammers have been used, in addition to an electric excavator fitted with a jackhammer, to dismantle activated concrete at KKN [361, 367] (see also Refs [449, 462, 499]).

6.3.4.4. Paving breaker and chipping hammer

The paving breaker/chipping hammer is a conventional civil engineering method and as such the technique is well developed (see also Section 6.2.2.17). These tools are widely used to remove concrete (and asphalt) by mechanically fracturing localized sections of the surface [130, 183] and are also very effective in the demolition of cast iron structures. They can be used either manually or from remote deployment systems, e.g. excavators or manipulators [361, 367, 448, 467, 468]. Possible industrial safety issues with these technologies are discussed in Ref. [207].

6.3.5. Electrical cutting techniques

Electrical cutting techniques are based on metal evaporation, in contrast with thermal cutting techniques which melt the metal. Electrical techniques do not generate any metal flow in the melt pool but they do generate a larger volume of aerosols, and hydrosols under water, compared with thermal techniques.

6.3.5.1. Electrodischarge machining (EDM)

EDM is based on the principle of the thermomechanical erosion of metals through the accurate control of sparks. It is applicable to all materials which possess sufficient electrical conductivity and is ideally suited to underwater applications [183]. This technique has been used in dismantling reactor internals at the BR3 decommissioning project for cutting the thick walled (76.2 mm) thermal shield and for some delicate ‘surgical’ operations, such as the removal of bolts which were difficult to access [130, 266, 267, 285, 287, 289–292]. The EDM technique was applied underwater at the VAK experimental BWR [197, 293, 428] to cut the sparger ring. Some R&D has been carried out at Harwell with the aim of speeding up the process and reducing the amount of secondary waste [370]. Applications of metal disintegration machining (MDM) (see Section 6.3.5.2) and EDM are extensively described in Refs [500, 501] (see also Ref. [429]). Figures 35 and 36 illustrate different EDM applications.

6.3.5.2. Metal disintegration machining (MDM)

MDM is similar to EDM except that the cutting pulses are generated by vibrating the electrodes [183] or by contact and retraction of the electrode from the workpiece. This technique has been used in mock-up trials for dismantling the reactor internals at BR3 [130, 266]. A comparison of MDM with plasma arc properties/applications is discussed in Refs [502, 503].

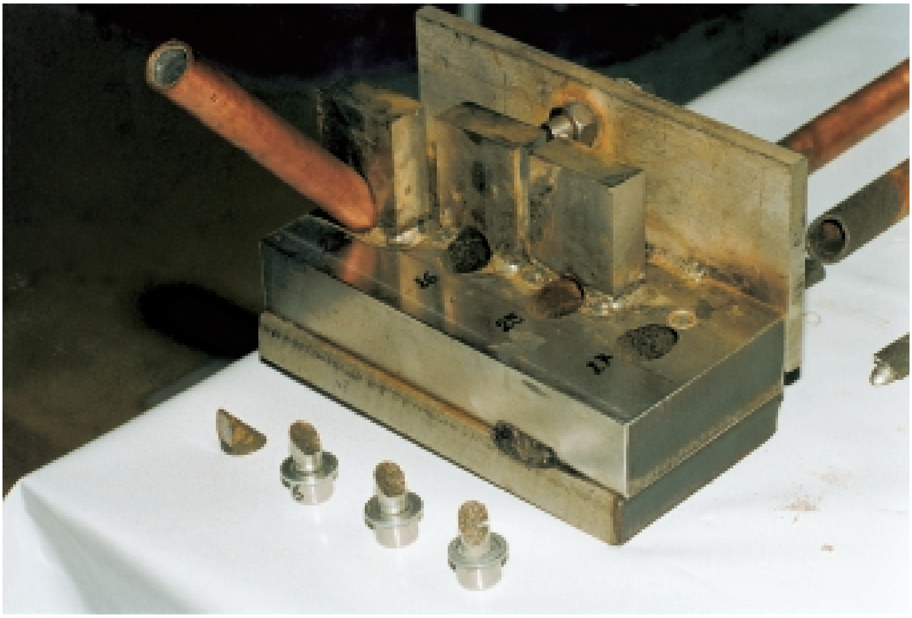

FIG. 35. EDM being tested on bolt cutting at the BR3 decommissioning project.

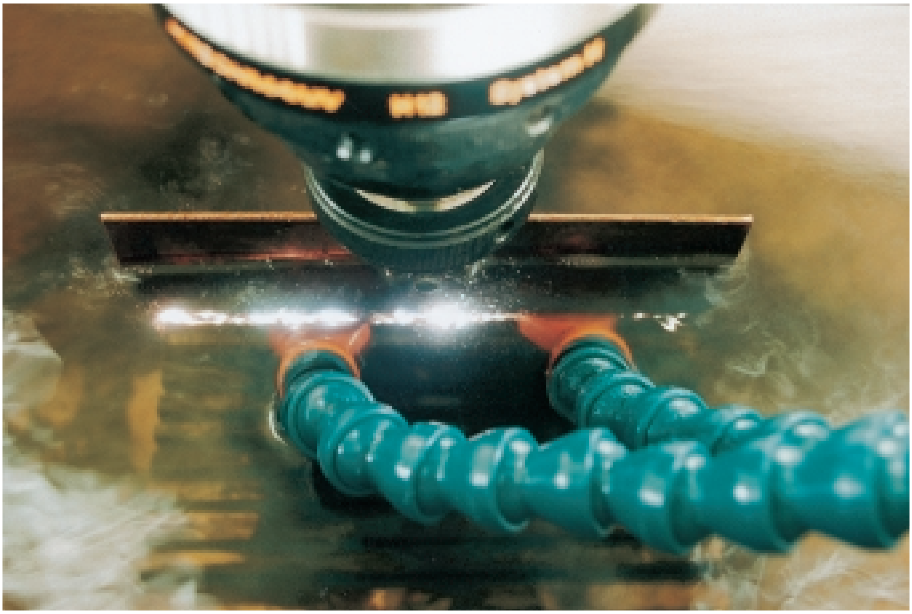

FIG. 36. EDM being tested on cutting thick gauge metal (underwater for remote use) at the BR3 decommissioning project.

6.3.5.3. *Consumable electrode*

The consumable electrode technique consists of a wire being continuously fed from a coil into the kerf, an arc being initiated by a short circuit between the wire and the workpiece [39, 183]. Three methods are reported in Refs [415, 485]:

— Oxygen jet cutting (mainly with mild steel wire)
— Water jet cutting (all metals)
— Water jet gouging (all metals).

A special prototype of a consumable electrode torch was developed and used at the JEN-1 reactor in Spain [197, 282, 283]. This technique has been tested for the underwater cutting of radioactive components at the Pegase facility in France [197, 477] where the maximum plate thickness that could be cut using a single power source and a 3 mm diameter wire was 100 mm.

6.3.5.4. *Contact arc metal cutting*

In the contact arc metal cutting process, the electrode is moved continuously towards the workpiece until contact is made between the two, thereby causing a short circuit. The electrode is then fed into the material to be cut. The high density of the current in the arc heats the workpiece, causing the material to evaporate [39, 197, 415]. This technique has also been tested at the Pegase facility for the underwater cutting of radioactive parts [197, 477]. The technique is being further developed via an EC R&D project [434] and at KRB-A for the removal of edges prior to the application of other techniques [421].

6.3.5.5. *Arc saw cutting*

Arc saw cutting uses a circular, toothless saw blade to cut conductive metals without making physical contact with the workpiece. This is achieved by maintaining a high current electric arc between the blade and the material being cut. It is effective in cutting high conductivity materials such as stainless steels, high alloy steels, aluminium, copper and Inconel [183]. It has been applied, under water and remotely operated, at JPDR for segmenting the body portion of the RPV [25, 132, 441, 443, 478, 504, 505] (Fig. 37). Arc saw cutting was proven to be effective in preventing the release of contamination, in addition to minimizing the radiation exposure of workers [480]. A comparison of arc sawing with other cutting techniques is provided in Refs [182, 429, 433, 434, 448].

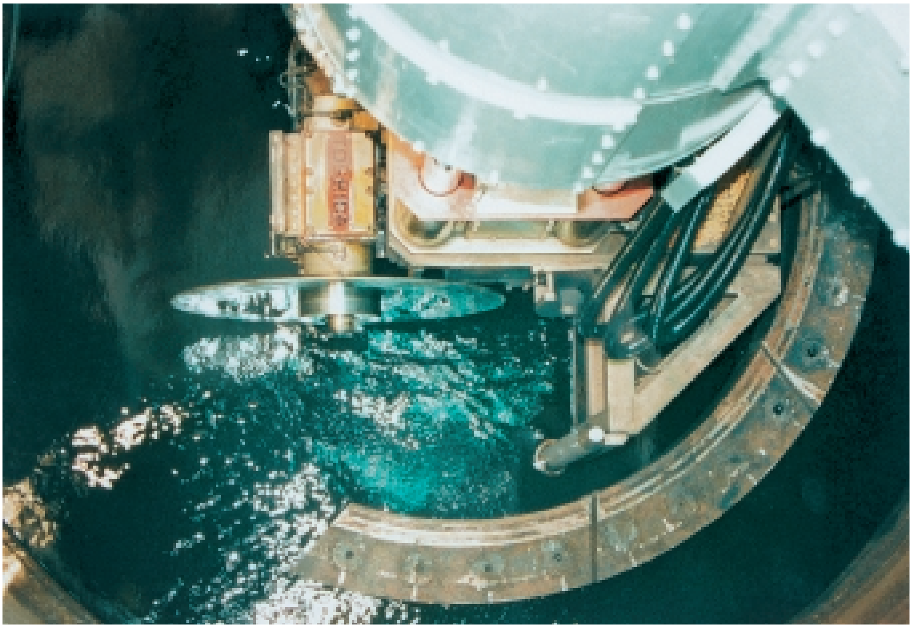

FIG. 37. Mast type arc saw cutting system employed in the vertical cutting of an RPV at the JPDR decommissioning project.

6.3.6. Emerging technologies

The following list presents the techniques that are currently being developed and/or which have not been fully evaluated as to their cost effectiveness [183, 250].

6.3.6.1. Liquified gas cutting

Liquified gas cutting is similar in principle to water jet cutting, except that the carrier medium is a liquified gas. Liquid nitrogen is being developed in the USA as a carrier medium [506]. The perceived advantages of this method include lack of a secondary waste stream; favourable economics; and absence of hazards from explosion, fire or oxidation.

6.3.6.2. Laser cutting

Laser cutting is a process by which a laser beam is used to heat locally a metal beyond its melting point, thereby cutting it. The technique can cut almost any material but is currently limited in its technical performance and by the high capital cost of the equipment [197, 429, 448, 507–509]. This process has been applied both in air and under water [509, 510]. To date, work in this area has focused on the use of the following types of laser: the CO and CO_2 in Europe [511] and Japan [512, 513], and the chemical oxygen–iodine laser in Japan [514]. The limited R&D work conducted to date in Japan has shown that optical fibre transmission would make laser transmission usable at a remote cutting location [486, 510, 515]. In addition, information and data have been gathered on aerosols, suspended particles and sedimented dross [184, 509, 516]. The laser technique has been applied at the VAK experimental BWR [197, 428] and produced a very thin kerf. The purpose of the study described in Ref. [517] was to evaluate the capacity of the pulsed YAG laser to cut thick metallic material and to compare it with CO_2 laser performance. A demonstration test to cut some 300 radioactively contaminated fuel storage tubes is described in Ref. [518]. Further R&D work is needed on this emerging technology [415, 486, 519].

6.3.6.3. Shape memory alloys

Shape memory alloys are novel materials in that they have the ability to return to a predetermined shape when heated, generating extremely large forces in the process. They can be used like expandable grout to break up concrete structures [183].

6.3.6.4. Electrical resistance

In the electrical resistance process, a large current is passed through the reinforcing rods of a concrete structure. The heat generated increases the rod dimensions and when the stress induced by the heating process exceeds the strength of the concrete, local failure will occur. This process is being developed for the BR3 reactor [130, 266, 286]. The results obtained so far show that the concrete can be fractured but that the dismantling still requires the use of an additional technique such as a jackhammer [467].

6.4. WASTE MANAGEMENT

6.4.1. Waste minimization, treatment, conditioning and packaging

Worldwide, many countries have developed comprehensive treatment strategies for waste arising from decommissioning projects. The starting point of these strategies is the production of an inventory of the radionuclides present, as these will dictate the operational, transportation and disposal practices to be employed during decommissioning and consequently will determine the costs of waste disposal [100].

Approaches to be exploited in order to reduce the volume of solid radioactive wastes include [423]:

- Segregation of non-contaminated and contaminated materials, particularly if this can be done at source;
- Use of on-site cleanup processes to recycle and reuse products whenever practicable;
- Use of super-compactors is widespread and has proved to be very effective [77, 520];
- Utilization of decontamination and decommissioning processes to prevent the spread of contamination or to recategorize waste forms;
- Recycling of products no longer needed on-the site;
- Planning and construction of the processes needed for the release of material from the site.

Conditioning and treatment techniques for liquids can include bituminization, drying, evaporation, cementation and incineration. Conditioning techniques for solids can include compaction, incineration, encapsulation within a solid matrix, direct packaging, dismantling and segmenting, melting, and chemical and biodegradation methods [39, 77, 245, 246, 521–528].

A system for dismantling, size reduction, decontamination, melting and encapsulation of decommissioning waste is described in Ref. [529]. A comprehensive description of the factors affecting the selection of a waste container and the packaging and how to optimize these processes is given in Ref. [530].

R&D activities in this field include the design of containers for waste items [424] (Fig. 38), in particular the large transport containers for intermediate level decommissioning waste [531] and the development of waste containers constructed from low level radioactive scrap steel [532]. Further development is needed in areas such as the treatment of waste originating from alpha contaminated material and non-ferrous scrap, the volume reduction of contaminated/activated concrete, the metallic coating of graphite parts to fix radionuclides, the recycling of reinforced steel in concrete and the recycling of slightly contaminated concrete [197]. For example, R&D activities on the treatment and conditioning of radioactive graphite by a series of controlled thermic desorptions in oxidizing and inert atmospheres and on the metallic coating of graphite by ionic deposition have been conducted in Spain and reported in Ref. [533]. A different conditioning technique for graphite bricks has been investigated in France [534]. A special waste treatment problem is that posed by sodium in fast breeder reactors [199] (see also Section 5.3.7).

The USDOE is currently undertaking development work on technetium and actinide solvent extraction methods, high temperature vacuum distillation separation

FIG. 38. Steel box for holding radioactive waste objects.

of plutonium waste salts, separation of tritiated water using membranes, and water soluble chelating polymers for the removal of plutonium and americium from waste water [87].

6.4.2. Recycling and reuse of materials, buildings and sites

A substantial quantity of waste generated from decommissioning activities could be recycled and reused [47]. Several hundred thousand tonnes of metal, concrete and other materials are expected to be disposed of worldwide [38, 535, 536] through the decommissioning of former weapon facilities and the future dismantling of power and research reactors. For example, dismantling of the Russian RBMK 1000 reactors will generate approximately 35 000 t of Cr–Ni steel [537], the major part of which would be suitable, after decontamination, for recycling.

6.4.2.1. Metal recycling

Melting is an adequate method of metal recycling for most decommissioning projects. A survey of existing and projected recyclable scrap inventories in the USDOE community is given in Refs [73, 76]. Practical demonstrations of the recycling of contaminated metals are being dealt with in USDOE D&D programmes [87, 538–543] and at US commercial facilities [544].

Recycling of steel and other materials has been reported from the decommissioning of the KRB-A facility [70, 374, 375]. Other references to German experience are given in Refs [367, 545–547]. Germany has a large industrial melting facility for radioactive materials which has been operational for a number of years [55, 56]. As the general size of melters for radioactive scrap metal is small compared with those for non-radioactive metals, the radioactive scrap has to be cut into pieces small enough to fit into the crucible. Cutting can be performed manually or, in the case of large quantities, in a more economical manner by using an automated process. A dedicated cutting facility to prepare metallic materials for melting is also in operation in Germany [548].

A report on the melting of uranium contaminated steel arising from the decommissioning of a fuel fabrication plant is given in Refs [549, 550]. Melting of steel, copper, brass and aluminium and the separation of different metals from electrical components by melting are reported in Refs [56, 551]. At Capenhurst, a decommissioning project dealt with over 160 000 t of suspect surface contaminated metals, concrete and other potentially hazardous materials. The significant nuclides were uranium and its daughter products, together with ^{99}Tc and ^{237}Np from the re-enrichment of reprocessed uranium. Over 99% of the total mass of materials were successfully treated and recycled via decontamination and melting [552].

A small melting facility for developing an aluminium recycling technique has been built at the JEN-1 reactor in Spain [282, 283] and a facility for melting aluminium and brass is in operation at Studsvik in Sweden [553, 554]. The melting of ferritic steel arising from the dismantling of the G2/G3 reactors has been investigated at a dedicated facility in France [555, 556] and Japanese test results on melting metals with low contamination levels and the manufacturing of new components are reported in Refs [253, 557–559] (Fig. 39). The recycling of Canada’s contaminated stainless steel fuel baskets is reported in Ref. [560] and an overview of industrial practices and investigative trials in the EU is given in Ref. [561].

In the Russian Federation, the first plant for metal melting was built at Belojarsk NPP (AMB-100 of BWR type) for the recovery of metals arising from plant decommissioning [245, 246]. The results were successful. To accelerate solutions to the problems of metallic radioactive waste in the Russian Federation, a special Federal programme entitled ‘The Treatment and Utilization of Metallic Radwastes’ was approved by the Government of the Russian Federation. In accordance with the programme, a pilot facility for remelting the radioactive scrap was built and put into operation in 1995. During 1995–1996 it melted about 100 t of stainless steel and cupro-nickel from the Leningrad NPP. This melting facility has been considered as

FIG. 39. The melting furnace at the Naka Energy Research Centre, Mitsubishi Materials Corporation.

the basic model of an industrial process [537], the main characteristics of the process and the proposed plans being given in Refs [246, 523, 537, 562]. An industrial scale melting facility is also planned for Chernobyl [563].

Although recycling is the main reason for melting metals contaminated with radioactivity, the melting process also results in some decontamination of the feedstock. This occurs as a result of separation of the different constituents of the melt, the degree of separation being controlled by the chemical and physical properties of the radionuclides present. For example, the melting of contaminated steel facilitates the separation of ^{137}Cs because Cs concentrates in the slag. On the other hand, ^{60}Co remains in the ingot, and therefore Co contaminated steel should be decontaminated before melting. In the case of neutron activated steels, Japanese test results on separating Co and Ni from Fe show that Co and Ni contaminated steel can be decontaminated by oxidation and reduction [558].

After the segmented steam generators of Sweden's Ågesta reactor were melted, measurements showed a reduced residual Co activity of 1–4 Bq/g [299]. Similarly, the experience gained from the melting of fuel element racks from a Spanish NPP showed that activity was reduced by a factor of three [564]. In Japan, nickel based alloys from reactor steam generators have been successfully melted by a continuous induction cold crucible process. Decontamination of the feedstock also occurred by the concentration of radioactive elements within the slag which formed on the surface of the melt [565, 566]. The possibility of melting metal after decontamination is also being evaluated at the BR3 reactor [266]. Use of melting technology for the homogenization and separation of radionuclides is also reported in Refs [47, 233].

Data on waste minimization, gained from melting techniques used in three facilities, are reported in Ref. [77]. After melting, the metals can be reused for a variety of purposes [559, 567, 568]. Initiatives now under way within the USDOE to utilize radioactive scrap metals to fabricate other products, such as radioactive waste shipping, storage and disposal containers, are described in Ref. [538].

Although the melting of metals contaminated with radioactivity can be regarded as a mature technology, R&D activities are still being performed to optimize the process or to overcome special difficulties. For example, R&D activities in Germany are reported in Refs [54, 569–571] and laboratory development of decontamination by melting is described in Ref. [572].

6.4.2.2. Concrete recycling

A process for the treatment of contaminated concrete has been investigated in the Netherlands [573, 574]. The conceptual process involves heating and simultaneously milling the concrete. The process effects the separation of the cementitious fines (representing a low volume stream, but containing most of the radioactivity) from the aggregate stream (the remaining high volume, low contaminated component). The latter is washed to remove residual contamination, enabling the aggregate to be reused. This concept, including the heating and milling of the concrete, has also been tested in Japan [558]. Results show that high quality aggregate can be recovered from concrete waste. Decontamination and recycling of concrete are also being investigated by the USDOE [87]. A study on how to deal with over 23 million cubic metres of concrete arising from the dismantling of USDOE buildings is described in Ref. [575]. Another US study is described in Ref. [576] and an EC study on the recycling of activated/contaminated steel scrap in concrete is reported in Ref. [172]. The mechanical and other properties of the reinforced concrete manufactured using scrap steel are investigated in Ref. [172] and preliminary conclusions given. Developments in Japan are given in Refs [558, 577].

6.4.2.3. Buildings and sites

The decision to clean up contaminated buildings and sites and the level of decontamination required depends on a number of factors. Experience in releasing sites and buildings exists in many countries where buildings [154, 578] or entire sites [367, 462] were released for restricted or unrestricted reuse. A US overview of decommissioned facilities/sites for which new productive uses were found after decommissioning is given in Ref. [579].

For small scale applications it might be a reasonable decision to reduce all the radioactivity to background levels. An example is the cleanup of a small shallow land burial site (40 m x 20 m) for low level radioactive waste formerly used by a research institute in the Netherlands. Because the waste site was very close to a densely populated area, the site was cleaned up by removing all the radioactive waste [580]. Other examples were presented at an international conference [581].

If the scale of the contamination is large, decisions to remove all radioactive waste may not be practicable. For instance, there are many contaminated sites, e.g. nuclear weapon facilities, that cover many square kilometres of land. The contamination may extend to all environmental media, as well as to on-site buildings and equipment. In these situations the decision to clean up, and to what level, depends on a comprehensive analysis of all aspects of the cleanup operation being undertaken in order to arrive at an optimal solution [50, 166].

6.4.3. Temporary storage

Temporary stores are an important component of the waste disposal strategy. These facilities are provided for a number of reasons, typically:

— As part of a strategy to enable the product form to achieve the specification required for acceptance in the final repository, i.e. vitrified glass;
— As temporary holding points until a final repository becomes available;
— As buffer stores, to enable optimization of the operation of the final repository.

A number of such facilities exist around the world, the following being a small selection.

As low level radioactive waste disposal facilities are not yet available in Canada, such waste is currently stored by the major waste generators in various engineered structures [582]. However, these storage facilities are not intended to store the entire stock of decommissioning waste that will be produced in the future. German experience, including the erection of dedicated storage facilities for some decommissioning waste, is given in Refs [583, 584].

The decommissioning and dismantling plan for Vandellos-1 NPP in Spain has allotted a dormancy period of some 30 years for completion of dismantling. During this period, it is proposed to (i) store the pre-conditioned graphite waste in a temporary radioactive waste storage area located in the low zone of the reactor building, and (ii) investigate management processes for the final disposal of the graphite [585].

6.4.4. Asbestos

Asbestos is a particular problem in both older nuclear and older non-nuclear facilities as the inhalation of even small quantities of asbestos fibre can result in lung disease. As a result of this, the removal and disposal of asbestos containing materials is subject to strict regulatory control, irrespective of the radioactive content. The techniques for the removal and direct disposal of asbestos are well developed, although the operational specifics may vary from country to country. In the USA, efforts continue to be made to develop a system for remotely removing asbestos from pipework, to convert asbestos containing material into a non-regulated material, and to develop an electromagnetic process for removing and separating hazardous and radioactive materials from asbestos [13, 87, 586, 587]. In the Russian Federation, tests on a semi-industrial scale have been undertaken for the compaction and melting of asbestos type insulation. Melting of the insulation resulted in a vitrified product and a 15–30 fold decrease in waste volume [246, 522]. Information on asbestos removal in Belgium can be found in Ref. [292].

6.5. ROBOTICS AND REMOTE OPERATION

Up until the early 1980s “only limited experience to date with the development and utilization of devices of this type...” existed [4]. The breadth of experience in

Europe expanded during the late 1980s and early 1990s as part of the Teleman project [588–590] and in the USA through the USDOE EM 50 Office of Science & Technology [591]. An overview of available remotely operated handling equipment was published by the IAEA in 1993 [11]. The purpose of this section is therefore to provide a series of references to developments and applications that have occurred since the above technical report was published.

Nowadays, in general, robotic wheeled/tracked vehicles are used for characterization, decontamination and dismantlement tasks. Other developments include: bridge mounted robotic platforms; power sources for mobile platforms; failure recovery equipment; automated separation technology; preprogrammed obstacle avoidance; programmed motions; teach/playback; voice control; transportable control systems; hardware (umbilical); laser based communication; force feedback; and flow, mass and volume sensors. All these are mature technologies [250].

According to Ref. [250], the following require further testing and evaluation: internal pipe/duct crawlers; light, medium and heavy duty long reach arms; arms with more than six degrees of freedom; remote/automated interchangeability; tool–arm interfaces; force limiters; multiple concurrent mobile platform controls; combined mobility/manipulation/end effector controls; sample management; data integration/fusion; fuzzy control; microwave communication; radio frequency based communication; 3-D vision; high definition television; directional audio; wall thickness measurement; laser range finders; and force controls.

Compact high capacity arms, multifingered end effectors, single human multiple vehicle control stations, human–robot symbiosis, imaging and image processing, proximity probes and positioning all require R&D according to Ref. [250].

According to the EC R&D programmes for 1984–88 and 1989–93, semi-autonomous manipulators should be adapted and tested with respect to specific dismantling tasks, as well as sensing systems and computer software. A telerobotic monitoring, decontamination and size reduction system was developed at the UKAEA for electropolishing of metal surfaces, clearance monitoring of concrete surfaces and glovebox size reduction [370]. Applications within the Sellafield decommissioning programme are described in Ref. [592]. At the Commissariat à l'énergie atomique, a master slave arm (RD 500) has been adapted for underwater use and successfully tested and is therefore qualified to perform underwater tasks [593].

A strategy known as contact deployment remote operation, which seeks to provide an acceptable and cost effective human–machine combination, is being exploited in the UK [592, 594]. As commercially available manipulator devices were not fully compatible with the constraints imposed by the WAGR environment, a custom-built, multiaxis manipulator was procured. Two different types of tool have

FIG. 40. Excavator being used for concrete removal at EBWR. Courtesy Argonne National Laboratory, managed and operated by the University of Chicago for the US Department of Energy under contract No. W-31-109-ENG-38.

been developed for deployment by the manipulator: a series of oxypropane cutting tools, and a series of electrically powered angle grinders. Over 30 handling systems have been developed for use at the WAGR, ranging from single mechanical plate grabs to remotely deployed vacuum cleaners. Large scale mock-ups have been used to test remote control devices, to optimize cutting parameters and to train operators [129, 445, 475].

The development at ORNL of a dual arm manipulation module to provide dexterous manipulation capability for remote characterization and D&D operations and to meet various deployment requirements is described in Ref. [595]. An automated, remote dismantlement system consisting of a set of end effectors and a number of auxiliary systems for task monitoring and waste control is being tested at ANL's CP-5 reactor [596].

Also developed within the USDOE D&D programme are diagnostics and data fusion of robotic sensors, a selective equipment removal system, and surveillance and maintenance risk and cost reduction evaluation methodologies [87]. The activated portion of the biological shield at the EBWR was removed using an electrohydraulic remote controlled jackhammer [423] (Fig. 40). Once the demolition work was completed, the machine was fitted with a bucket scoop and used to load the concrete rubble into shipping containers. A US market survey of commercially available manipulators, end effectors and delivery systems for reactor decommissioning activities is provided in Ref. [597].

A series of remote controlled devices has been developed at the University of Hannover in Germany [598]:

— An underwater tool carrier system (ODIN 1) designed to dismantle the steam dryer at the KRB-A reactor;
— A cutting device (RAMSES) developed at the KRB-A reactor to cut the internals of the reactor core, the head of the reactor vessel, the RPV steam drier and the standpipes using a small plasma torch [277, 371, 599];
— A combination of an ultrasonic sensor and an eddy current sensor (INDUS) to measure thickness, distance and orientation;
— A seven axis manipulator (ZEUS);
— A free diving handling system (FAUST);
— A wall climbing robot (HYDRA).

Additional information on German experience is provided in Refs [600, 601].

A comprehensive description of the French programme and experience on the use of robotics for decommissioning purposes is given in Refs [602, 603] and a review of Russian experience in the remote deployment of decontamination and dismantling systems is detailed in Ref. [244].