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Synthesis Report on Management of Metallic Waste Streams

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Abstract

The aim of this report is to present a synthesis of the work completed within PREDIS WP4 Task 4.3 on metal decontamination approaches. It details (1) the inventory of radioactive metallic waste produced by European countries, highlighting the need for innovation to address upcoming waste arisings; (2) the methodology to determine the secondary wastes produced by a metal treatment process; (3) updated technology datasheets for metal decontamination and melting approaches and (4) the methodology for, and the outcome of the value assessment process developed in THERAMIN and refined within PREDIS, as applied to the technologies developed in WP4, thus supporting decision-making and implementation by End Users.

The first part of Deliverable 4.2 summarises the state-of-the-art in terms of mechanical, chemical and thermal treatment routes for radioactive metallic wastes, and demonstrates the variety of technologies available on the market or in development (such as PIVIC). Non-nuclear melting technologies are also detailed in this report (such as rotary furnace or Electric Arc Furnace Melting).

Three decontamination technologies were further studied and developed in PREDIS WP4: two decontamination gels (Aspigel and Electrolytically Assisted Surface Decontamination gels), and one chemical oxidation technique, COREMIX-HP. The economic, environmental and safety impacts of these three technologies were evaluated to assess whether the project was successful and beneficial to End-Users. The value assessment process was applied to provide a rigorous and systematic impact assessment, against a baseline representing current or planned waste management practices.

The conclusions were unequivocal. Both COREMIX-HP and gel decontamination were found to lead to significant cost savings, driven by waste volume reduction and metal recycling, and made possible in some instances by surface decontamination. Both avenues present neutral to improved environmental outcomes when compared against the current option, which is size reduction and disposal as ILW. Secondary waste management (e.g. spent ion exchange resins generated by the COREMIX-HP process) and disposal were identified as areas requiring further research and development, although no unsurmountable issues were identified.

Some of the waste streams identified in the inventory do not currently have a management route; the approaches developed in PREDIS WP4 can demonstrably offer solutions to treat and condition these waste streams, whilst reducing waste volumes and costs compared with conventional approaches. A forward work programme to address uncertainties associated with the disposability of some of the secondary wastes is proposed under EURAD-2.

This version of the report has been updated addressing comments by external reviewers Eric Bourcier (expert in metallic decontamination) and Eileen Lagegger (DMT).

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Notification

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LIST OF ACRONYMS

AC	Alternative Current
ALARP	As Low As Reasonably Practicable
Ames-LMIT	Ames Laboratory and Lockheed Martin Idaho Technology
BWR	Boiling Water Reactor
CCIM	Cold Crucible direct Induction Melting
CARLA	Centrale Anlage zum Recyclieren Leichtaktiver Abfälle (Germany)
CEA	Commissariat à l'Énergie Atomique et aux Énergies Alternatives (France)
CENTRACO	CENTre de TRAltement et de COnditionnement
CORD	Chemical Oxidation Reduction Decontamination
COREMIX-HP	Chemical Oxidation REDuction using nitric permanganate and oxalic acid MIXture followed by Hydrogen Peroxide treatment
CSA	Centre de Stockage de l'Aube (France)
DC	Various Direct Current
DF	Decontamination Factor
DTM	Difficult To Measure [radionuclides]
EAF	Electric Arc Furnace
EASD	Electrolytically Assisted Surface Decontamination
EC	European Commission
EDTA	Ethylenediaminetetraacetic Acid
EDX	Energy Dispersive Using X-Ray
EPRI	Electric Power Research Institute (USA)
EUG	End User Group
FPH	Fortum Power and Heat Oy (Finland)
GDF	Geological Disposal Facility
GERTA	Grosstechnische Einrichtung zum Recyclieren toxischer Abfälle (melting facility) (Germany)
HEPA	High Efficiency Particulate Air
HIP	Hot Isostatic Pressing
HLW	High-Level Waste
HP	Hydrogen Peroxide treatment

IAEA	International Atomic Energy Agency
ICV	In-Container Vitrification
IEX	Ion-Exchange Resin
ILW	Intermediate-Level Waste
IMT Atlantique	École nationale supérieure Mines-Télécom Atlantique Bretagne Pays de la Loire (France) – Institut Mines Télécom Atlantique
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LL	Long-Lived
LLW	Low-Level Waste
LLWR	Low Level Waste Repository (UK)
MEDOC	Metal Decontamination by Oxidation with Cerium
MP	Measuring point
NAGRA	National Cooperative for the Disposal of Radioactive Waste (Switzerland)
NDA	Nuclear Decommissioning Authority (UK)
Nd:YAG	Neodymium-doped Yttrium Aluminium Garnet
NNL	National Nuclear Laboratory (UK)
NPP	Nuclear Power Plant
PACT	Plasma Arc Centrifugal Treatment
PAM	Plasma Arc Melter
PCB	Polychlorinated biphenyls
PCM	Plutonium-Contaminated Material
POCO	Post Operational Clean Out
PPE	Personal protective equipment
PVC	Polyvinyl Chloride
PWR	Pressurized Water Reactor
SEM	Scanning Electron Microscopy
SIAL	Sludge in an Inorganic Aluminosilicate matrix
SL	Short-Lived
SNETP	Sustainable Nuclear Energy Technology Platform
SS	Stainless Steel

THERAMIN	Thermal treatment for radioactive waste minimisation and hazard reduction (EC Project)
TRL	Technology Readiness Level
UJV Rez	Ústav jaderného výzkumu Řež – Nuclear Research Institute (Czech Republic)
UV	Ultraviolet
VLLW	Very-Low-Level Waste
VTT	Technical Research Centre of Finland
WAC	Waste Acceptance Criteria
WMO	Waste Management Organisation
WP	Work Package
XRD	X-ray Diffraction

1 Introduction

1.1 Background to the PREDIS Project

The PRE-DISposal management of radioactive waste (PREDIS) project is a four-year programme of research and development targeting the treatment and conditioning of low-level and intermediate-level radioactive wastes (metals, solid organics, liquid organics, and cemented waste) [1]. The main objectives of the PREDIS project are to:

- develop solutions for the future treatment and conditioning of waste for which no adequate or industrially mature solutions are currently available;
- improve existing solutions to make them safer, cheaper or more effective; and
- analyse material and packaging requirements and associated Waste Acceptance Criteria (WAC) for pre-disposal and disposal activities.

The PREDIS project consists of the following Work Packages (WPs):

- Work Package 1 - Management and dissemination.
- Work Package 2 - Strategic implementation.
- Work Package 3 - Knowledge management.
- Work Package 4 - Innovations in metallic waste treatment and conditioning.
- Work Package 5 - Innovations in liquid organic waste treatment and conditioning.
- Work Package 6 - Innovations in solid organic waste treatment and conditioning.
- Work Package 7 - Innovations in cemented waste handling and pre-disposal storage.

The relationship between the work packages and the overall PREDIS project is shown in Figure 1. WPs 4-7 comprise the primary technical topics within PREDIS. The overall strategy is considered in WP2 and is informed by the technical topics. WP3 concerns knowledge management, this includes designing and defining training programmes covering the content of WP4-7, gathering the state-of-the-art on pre-disposal activities and interfacing with the EURAD project to ensure consistency. WP1 concerns project management and dissemination and spans all of the work packages.

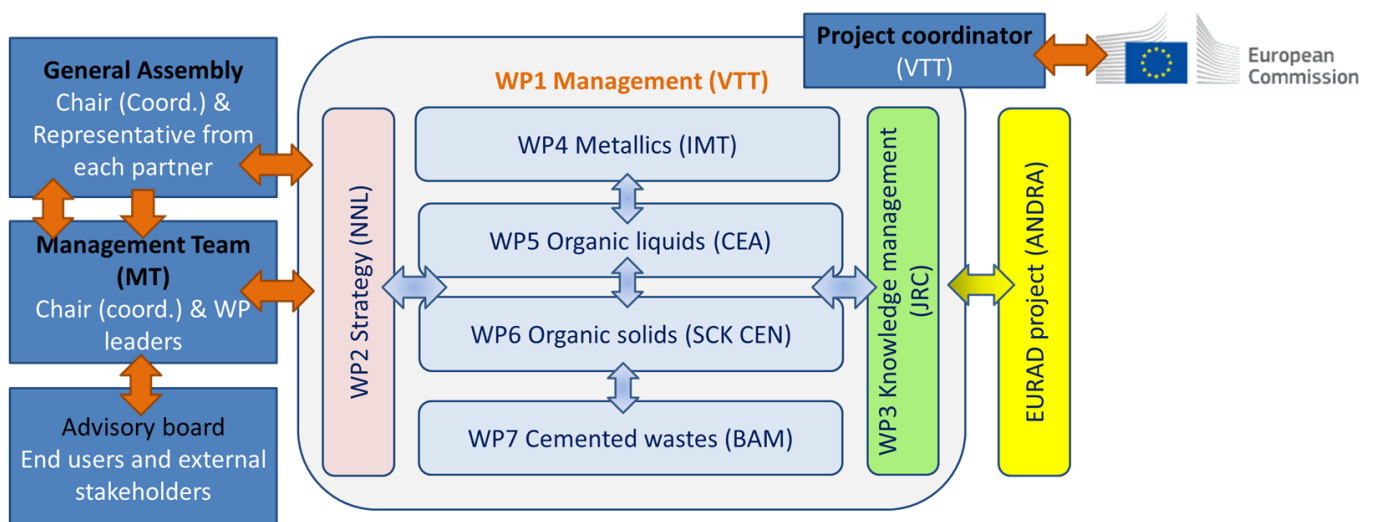


Figure 1: Relation between work packages within the PREDIS project.

1.2 Scope and Objectives of PREDIS Work Package 4: Management of Metallic Waste Streams

WP4 targets the treatment and conditioning of metallic radioactive wastes. The need for this work package is linked explicitly to the foreseen end-of-service-life for the current fleet of European civil nuclear power plants and the accompanying decommissioning processes, which are expected to generate thousands of tonnes of radioactive metallic waste on top of existing inventories. In light of this, there is a need to develop more effective decontamination and remediation processes for metallic wastes, as well as optimising routes for recycling and reuse. The main objectives of WP4 as laid out in the PREDIS grant agreement [1] are to:

- Minimise the amount of metallic waste to be sent to disposal facilities through the use of new and/or optimised treatment and decontamination processes, and more effective characterisation.
- Contribute to the development of a new reference, stable and safe solution for the storage and final disposal of metallic wastes, including reactive metals such as aluminium and beryllium.
- Estimate the potential scale of the opportunity for management of European metallic wastes, including quantification of the benefits in economic terms and application of the waste hierarchy.

The work package is split into the following seven tasks:

- Task 4.1 – WP management.
- Task 4.2 – Gap analysis.
- Task 4.3 – Defining Europe-wide needs and opportunities for management of metallic waste streams.
- Task 4.4 – Development and optimisation of decontamination processes.
- Task 4.5 – Optimisation of metallic waste characterisation and procedures for waste minimisation and recycling.
- Task 4.6 – Encapsulation of reactive metals in magnesium phosphate cement-based matrices.
- Task 4.7 – Dissemination.

Tasks 4.2-4.6 comprise the technical work of the WP with Tasks 4.4-4.6 having large experimental components and Tasks 4.2 and 4.3 being more desk-based. Tasks 4.1 and 4.7 are intended to support the management, coordination and dissemination of the core technical work.

This report focuses on Task 4.3 which:

- Synthesizes available **inventory information** on amount and nature of radioactively contaminated and/or activated metallic waste in Europe, both existing and in the future, national priorities and waste management needs, and regulations.
- Identifies, quantifies and optimises the amount of secondary waste, and provides **guidance for secondary waste management**.
- Compiles the **state of the art** on:
 - Metallic waste decontamination processes and secondary waste arisings, including constraints and decontamination efficiency for different processes.
 - Characterization processes and methodologies, applied to specific problematic of metallic waste management and clearance.

- Management solutions for reactive metals.
- Establishes **strategic analysis (costs and benefits)** of the potential opportunities for metal decontamination and melting, focusing on technologies studied in WP4, and **identification of gaps in coverage** across Europe.

1.3 Objective of this Report

The objective of this report is to present a synthesis of the work completed within PREDIS WP4 Task 4.3 on metal decontamination approaches. It details:

- The inventory of radioactive metallic wastes in a range of European countries.
- Technology datasheets for established and new metal decontamination and melting approaches, identifying advantages and potential challenges.
- The potential for application of conventional metal melting technologies to radioactive waste treatment.
- The methodology, and the outcomes of the value assessment process applied to techniques developed within PREDIS WP4.

This report is structured to support decision-making and implementation by End Users.

1.4 Structure of this Report

The remainder of this report is set out as follows:

- Section 2 describes the inventory of metallic waste requiring treatment, obtained from WP4 Partners.
- Section 3 details the methodology used to identify and optimise secondary waste management within WP4.
- Section 4 presents datasheets for a range of different metallic waste decontamination technologies.
- Section 5 presents the economic and environmental impacts of decontamination and metal melting, including the results of a Value Assessment completed for three of the technologies investigated within WP4.
- Section 6 summarises the conclusions of PREDIS Task 4.3.

2 Inventory of Metallic Waste and Challenges Associated with their Management

An inventory of metallic waste was gathered to size-up the commercial opportunity from and the need for novel metallic waste treatment technologies in Europe and to confirm the types of metallic waste that should be studied in PREDIS. These data were presented in PREDIS Deliverable 4.1 [2].

Results were obtained from CEA (France), Fortum Power and Heat (Finland), VTT (Finland), UJV Rez (Czech Republic), Nagra (Switzerland) and DMT (Germany). This was a limited sample, but it is considered to be indicative of the types and volumes of metallic waste that could arise from other countries.

2.1 Waste types

Figure 2, from [2] shows an overall summary of the different metallic waste streams identified by WP4 Partners and End User Group (EUG) members, broken down by the general type of waste. As it was not possible to differentiate the German wastes, they are not integrated into Figure 2 [3].

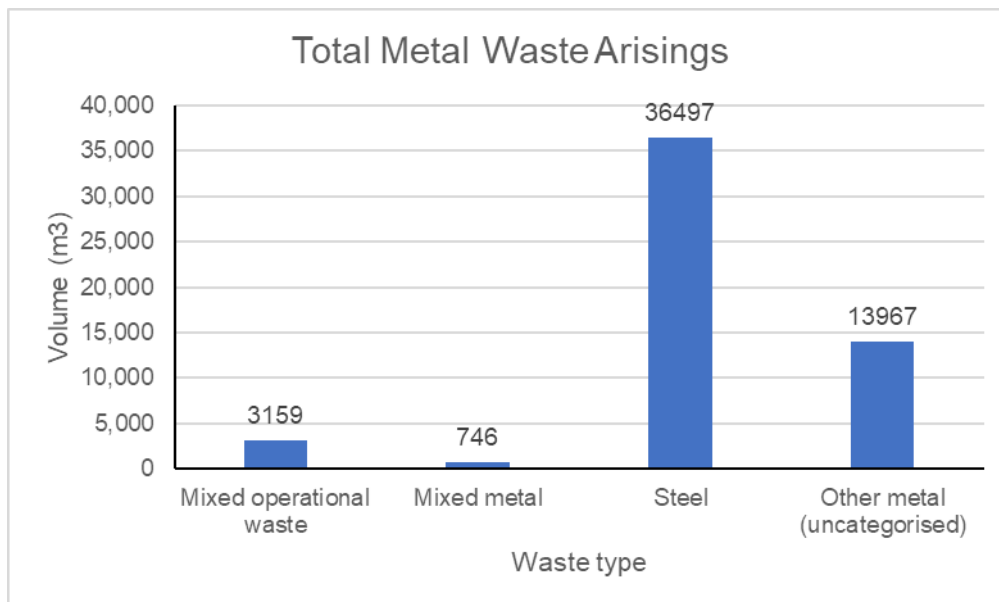


Figure 2: Metallic waste volumes identified in the inventory responses, grouped by general waste type.

Overall, it is clear from this summary that the dominant type of metallic waste present in Europe is steel, predominantly material arising from decommissioning and demolition of reactor buildings. Important quantities (non-quantified to-date) of metallic waste (usually nickel-based alloys) will also arise from steam generator replacement or decommissioning across Europe. In Figure 2, note that uncategorised waste (other metal) shows the arisings from CEA where insufficient detail was available to group the wastes by type, but the main wastes arising from CEA are mixed operational wastes.

Steel is one of the main metallic waste types being considered for decontamination and conditioning in WP4. Therefore, these inventory responses reinforce the relevance of the PREDIS work on decontamination of steel alongside the other treatment approaches summarised in this report, and the importance of developing methods to manage this waste.

2.2 Times of arising

One important consideration when thinking about developing treatment facilities is the time of waste arisings. From the information provided in the inventory responses, it is possible to differentiate between waste that has been created (and is being stored) and waste that will arise in future (for

example from decommissioning). Figure 3 shows the volumes of waste by time of arising, where this information was available. Note, the timing of arisings from CEA were uncertain, so were assumed to be current wastes, and included in that total. It was assumed that the current metallic waste stocks available in Germany comes from the 28 reactors that have reached the end of their service life and are currently being decommissioned [4]. As the values obtained were in kilogrammes [3], to convert them to volume data it was assumed that the density of steel is 7,850 kg/m³.

From this compilation, it is clear that just less than half of the total inventory is yet to arise, the bulk of this coming from decommissioning of reactors in Switzerland.

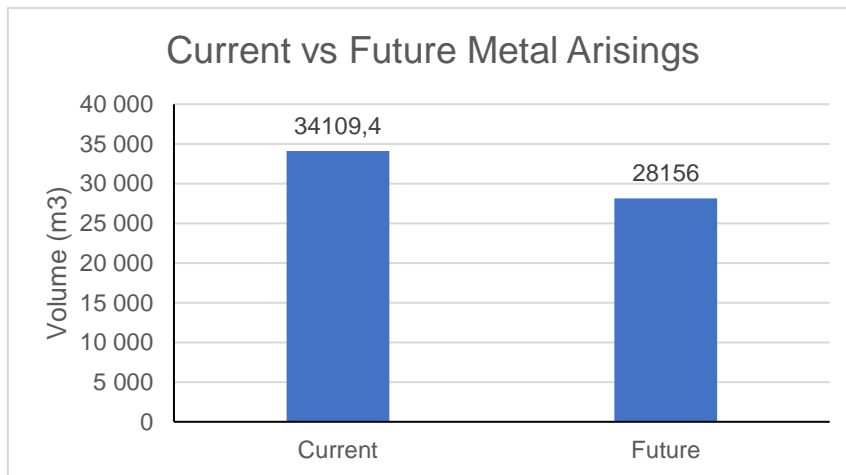


Figure 3: Current and future metallic waste volumes.

2.3 Contamination and activation

Decontamination is a suitable process for treating contaminated metals, whereas activated metal cannot be fully decontaminated and is likely to require disposal (though melting may help to reduce the activity levels). It is possible from some of the inventory responses to assess whether the bulk of the metallic waste is predominantly contaminated or activated, and this is shown in Figure 4. Note however, that not all respondents provided information on whether waste was contaminated or activated, so this picture is incomplete (i.e. the total here does not equal the total volumes in Figures 2 and 3 above and most of the CEA waste is excluded). It is assumed that the metal from Germany is only activated [3].

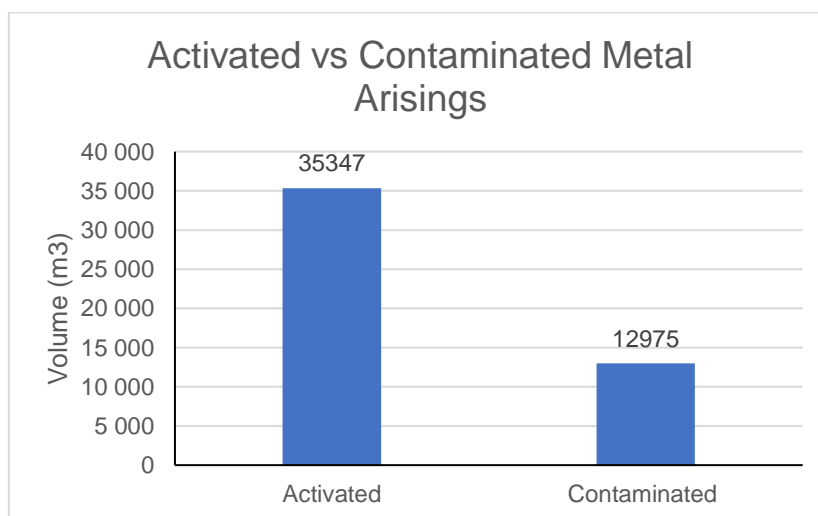


Figure 4: Volumes of activated and contaminated metal identified in the inventory responses.

From the response shown in Figure 4, it is evident that the majority of waste identified by the respondents was activated metal, but large volumes of contaminated metal were also reported. Note, however, that the balance of activated/contaminated may be artificially skewed due to the inclusion of a single large inventory stream reported by Nagra (26,281 m³), which was identified as being activated and the German inventory which was assumed to be activated [3].

Overall, the inventory data supports the approach in WP4 of investigating both metal decontamination processes and metal encapsulation for activated materials, from which the activity cannot be readily removed. Thermal processes (such as metal melting) may also be viable treatment options and, although not being directly developed in WP4, melting processes have been reviewed within this report.

2.4 Conclusion

Overall, it appears that large volumes of metallic waste are currently being generated by PREDIS partners and EUG organisations. Some management routes have previously been established (such as melting for example) or were developed further within PREDIS WP4. Technology datasheets for these technologies are presented in Section 4.0 of this report. The strengths and weaknesses in terms of economic and environmental impacts are assessed and discussed in Section 5 for those developed in PREDIS.

3 Secondary Waste Management

A methodology on secondary waste management was presented in Milestone MS24 [5] to allow experimental Partners within WP4 to detail for each technology the sources of secondary waste and amounts generated, how these can be reduced in scaling up to industrial scales and how these wastes can be managed.

3.1 Introduction and Definition of Secondary Wastes

Secondary wastes correspond to the waste materials that are generated as a consequence of treatment or decontamination activities [6]. Secondary wastes can include solid material and sludge, as well as liquid and gaseous discharges, but are not generally considered to include the primary wasteform.

Metallic waste treatment processes can be broadly grouped into 'treatment and conditioning processes' and 'decontamination processes' with some overlap between the two.

3.2 Secondary Waste Arisings from PREDIS WP4 Technologies

WP4 is aiming to develop and optimise decontamination technologies for treatment of metallic waste. An important component of the optimisation process is increasing the process efficiency, thus reducing the generation of secondary wastes.

The guidance given within MS24 highlighted the importance of a detailed inventory of the initial waste being treated (including information on volume, absolute and radionuclide specific activity). To allow a full mass and activity balance to be developed, the guidance showed that it is important that, in addition to characterisation of the primary product (the treated metal), detailed sampling and characterisation is carried out of all secondary waste streams.

The work done in WP4 relating to identification and characterisation of secondary wastes and any optimisation measures is summarised in the relevant technology datasheets in Section 4.

4 Description of metallic waste treatment technologies

This section comprises a series of datasheets describing metal treatment technologies, including mechanical and chemical decontamination and melting. The datasheets are provided for the technologies that were developed within PREDIS WP4 and alternative technologies not being directly studied in PREDIS, but potentially of interest to WP4 Partners and End Users. Technologies studied and developed in PREDIS WP4 are identifiable by the presence of the PREDIS logo. Drafts of some of the Technology Datasheets included in this report were first presented in PREDIS WP4 Milestone MS23 [7].

The main goal of these techniques is to treat the metal to decrease its activity, enabling recycling or diversion according to the waste hierarchy. For contaminated metals, in general, the activity is concentrated in an oxide layer at the surface of the metal [8]. In this case, the metal can be treated by mechanical (physical abrasion) or chemical (chemical dissolution) decontamination to decrease its activity before melting, reuse/recycling if possible or storage/disposal as a less active waste (meeting waste hierarchy requirements).

As an example, Figure 5 presents the composition of the oxide layer for contaminated metallic waste from decommissioning of PWR (Pressurized Water Reactor) and BWR (Boiling Water Reactor) steam generators.

Oxide			Base Metal
	B	C	Austenitic SS Inconel 600 Incoloy 800
A	B	C	Austenitic SS

PWR:
Activity in both B & C
Probably need to remove both layers for reasonable decontamination

BWR:
>90% of activity in A & B
Reasonable decontamination if only A & B removed

Layer A – Deposited oxide (Fe as Fe³⁺) containing predominantly:
Fe₂O₃ and FeOOH

Layer B – Deposited oxide (Fe as Fe³⁺ and Fe²⁺) containing predominantly:
Fe₃O₄, NiFe₂O₄ and Ni_xFe_{3-x-y}Cr_yO₄ (y<1)

Layer C – Grown-on oxide (Fe as Fe²⁺, higher Cr) containing predominantly:
Ni_xFe_{3-x-y}Cr_yO₄ (y>1), FeCr₂O₄, NiCr₂O₄ and Cr₂O₃

Figure 5: Summary of surface film composition in contaminated metals arising from PWRs and BWRs [8]

The following datasheets provide an overview of the decontamination techniques available on the market or in development. Each datasheet presents:

- A description of the technology and how it is applied in the context of metal treatment.
- The types of materials that can be treated, including any limitations or constraints.
- A description of the product, including the decontamination efficiency.
- A description of any secondary wastes, including their volumes, characteristics and how they can be managed.
- References.

Note that the datasheets are presented as standalone documents. All references are contained within the datasheet so reference numbering within the subsequent datasheets is not linked to the

reference numbering used in the main report. Figure and table numbering is also specific to each datasheet, to enable them to be extracted for individual use by PREDIS Partners and End Users to support options studies and Value Assessments for metal decontamination of their specific waste streams.

4.1 Mechanical decontamination techniques

Different mechanical decontamination techniques are used to treat metallic wasteforms, including jet washing, sand blasting, dry ice blasting and laser decontamination:

4.1.1 Jet washing

Technology name: Jet washing

Technology description

Jet washing is a surface decontamination technique that utilises a jet of water to physically remove a thin contaminated layer from the surface of a material. The technique can be used at different levels: low, medium, high and ultra-high pressure; but is usually operated at high or ultra-high pressure typically from 345 to 3000 bar [1, 2]. It is important to determine the right flow rate/pressure for this kind of decontamination. Where large surfaces need to be decontaminated, high pressure water jets have been found to be efficient and easy to use, both in terms of contamination removal and the processing time required [3].

Jet washing can remove loosely adhered surface contamination (such as oils) with water alone. However, for the removal of more strongly adhered contamination or surface layers (such as paint or corrosion products) the process can be enhanced by the addition of chemical detergents, or abrasive solid particulates into the water jet (e.g. grit embedment) [1, 3]. Alternatively, higher temperature water can be used, which can help to penetrate deeper into the metal surface [1]. A first step such as chemical decontamination can also be included.

Operating principles

In the core zone of the jet stream, the flow properties, such as pressure and flow velocity, are constant along the jet axis. In the transition zone, the flow velocity is a function of the jet, and has high values at the centre of the jet and decreases as it approximates the rim of the jet. In the droplet zone, water drop formation occurs due to external friction, air entrainment, and internal turbulence. The water droplets impinging on the target surface create impact forces. During the water jetting, each small area of the surface experiences repeated impacts from the water droplets [3].

The most commonly used types of nozzles are round-jet and flat-jet nozzles. The former allows good decontamination efficiency over larger areas at a greater standoff distance; in contrast with the flat-jets, which are used at smaller distances to treat large areas. The round self-rotary type of nozzle has recently become popular in the industry, as it exhibits excellent surface cleaning efficiency for difficult and irregular surfaces. The rotating action comes from the nozzle, not the barrel, so the water force is focused in the droplet zone of the jet where it is most effective. Numerous studies have revealed that the width and depth of decontamination, and thus material loss, increases with increasing nozzle diameter [3].

Experimental observations have shown that there exists an optimal standoff distance at which the volume of material removal is the greatest at a given traverse rate and water pressure. It was shown that the cleaning rate increases with the increase in standoff distance until it reaches the maximum at a certain standoff distance, after that the cleaning rate declines with increased standoff distance. The optimal standoff distance is related to the bulk material being water jetted, the jet structure and properties, and a range of operational parameters such as nozzle size, water pressure, traverse speed, etc. Care must also be taken if the standoff distance is too small as it will cause damage to the bulk material [3].

The traverse rate is the speed at which the water jet operative moves the water jet across the surface being decontaminated. Experiments show that width or depth of material removal

decreases with the increase of traverse rate. An increase of traverse speed may result in a decrease of energy or droplet numbers which are delivered per unit of coating area [3].

The impact angle is the incident angle between the water jet and the surface being decontaminated. The highest degree of decontamination is achieved when the impact angle is between 30°- 45°. A perpendicular angle (90°) shows the worst cleaning results [3].

Industrial Examples

Jet washing techniques can be employed in a wide range of locations across nuclear sites. Large surfaces such as walls and vessels may be decontaminated in situ. For smaller items however, pressure washing is often conducted in sealed treatment chambers, such as the “Water Jet Cabine” produced by FerroECOBlast, shown in Figure 1. These chambers have the advantage of allowing the operator to work in an enclosed chamber, reducing the risk of overspray and backsplash contaminating near-by surfaces, while also allowing spent water (secondary waste) to be collected and potentially filtered and recirculated for reuse.

Water jetting was also used at the Sellafield site to decontaminate nuclear plant steels, but results are mixed; operational variability such as pressure and incident angle on the effectiveness of decontamination of Type 304 austenitic stainless steel were investigated in [3]



Figure 1: The FerroECOBlast Water Jet Cabine [4]

Technical maturity:

TRL 9 – Proven technology in an industrial environment.

Types of metals treated (including limitations on size and activity)

Jet washing can be used to treat a wide range of materials, including most types of metals. The only limitation is that the material must have sufficient mechanical strength to withstand the force of the jet without deforming, cracking or shattering. Various parameters are pertinent for the process such as: the distance between the pipe nozzle and the material to be decontaminated, the temperature and the nature of the solid or liquid [3].

Jet washing is a surface treatment technique, so is not appropriate for treating metals with inaccessible contaminated surfaces, bulk material contamination or activation.

Product characteristics (including decontamination efficiency)

Jet washing produces a material with significantly reduced levels of surface contamination. The decontamination factor for jet washing can be as high as 20x [1], meaning treated items may be sufficiently decontaminated to be classified as very low-level waste, or even material suitable for clearance and release into the open market.

In the case of the addition of abrasive solid particulates, care must also be taken not to introduce contamination deeper into the bulk steel or to spread the contamination along surfaces [3].

Secondary wastes

The main secondary waste associated with the jet washing process is the spent water (with or without additives). This liquid will contain both dissolved radionuclides, and potentially some suspended solids which must be filtered and treated separately. The water needs to be captured and contained to prevent it leading to uncontrolled contamination of the facility or wider environment [5]. Different approaches to capturing the waste have been developed including the use of vacuums to suck up the contaminated water as it leaves the surface being treated. Alternatively, the jet washing process can be conducted within a specially designed treated cell (such as the FerroEcoBlast [4] setup shown in Figure 1). This treatment cell can incorporate controlled drainage allowing the spent water to be safely captured and either stored (open loop) or recycled back into the jet (closed loop), to reduce overall water usage.

Once produced the contaminated water may require treatment prior to discharge, likely creating additional secondary wastes, such as ion exchange resins or slags if the water is incinerated. Moreover, in the case of using abrasive solid particulates, recycling these to reduce the volumes of secondary waste produced must be considered.

The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment.

References

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- [2] <https://www.nje.fr/decontamination-as-protek/> [accessed 06/24]
- [3] Irina P Nedyalkova (2018) Decontamination of Nuclear Plant Steels, PhD thesis, University of Manchester
- [4] <https://ferroecoblast.com/products/product/water-jet-cabine-decontamination-of-radiological-wastes> [accessed 07/21]
- [5] IAEA (1979) Decontamination of Operational Nuclear Power Plants, IAEA-TECDOC-248

4.1.2 Sand blasting

Technology name: Sand blasting

Technology description

Dry abrasive blasting (Figure 1), commonly termed sand blasting, uses abrasive materials suspended in a medium that is propelled onto the surface being treated [1]. This technique results in a uniform removal of surface contamination [2]. Removed surface material and abrasive are collected and placed in appropriate containers for treatment and/or disposal [1].



Figure 1: Dry abrasive blasting [3]

Operating principles

Dry abrasive-blasting systems can provide very high decontamination factors. However, the longer the operations are continued, the more destructive they are. Moreover, care must be taken not to introduce the contamination into the material surface (hammering effect) in order for the ability to meet clearance levels not to be jeopardised [2]. The system uses a combination of abrasive media and compressed air and is normally applied in a self-contained, leakproof, stainless-steel enclosure [2].

The abrasive particles are pneumatically accelerated and forcefully directed against a surface. These high speed abrasive particles can be used to remove contaminants and unwanted materials or irregularities from a surface and to condition the surface for subsequent finishing [4].

Radioactive waste is mechanically separated from the cleaning media, e.g. by cyclone/centrifuge separation or sieving [1]. Recirculation of abrasives allows the minimisation of secondary waste. Materials such as oil and grease, or obstructions close to or bolted to components must be removed before application, and precautions should be taken to stabilise, neutralise or remove combustible contaminants, because some abrasives may cause some materials to detonate or generate dust explosions. Static electricity may be generated during the blasting process; therefore, the component being cleaned, or the treatment equipment, should be grounded [2].

Industrial Examples

Equipment is available from specialist suppliers, including FerroEcoBlast Europe. Industrial equipment is also available for remote operation [5].

Technical maturity:

TRL 9 – Proven technology in an industrial environment.

Product characteristics (including decontamination efficiency)

An example of the decontamination efficiency is given below:

Table 1: Decontamination efficiency [2]

Efficiency	Very high
Plates	57.4 kg/h – 2.8 m ² /h
Profiles	127.7 kg/h – 1.8 m ² /h

Results published in [6] regarding the decontamination of the inner surface of steam generator tubes are detailed in Figure 2. This shows that improved decontamination factors are obtained with increased treatment time and blasting distance.

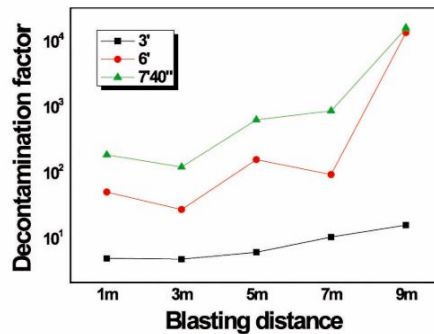


Figure 2: Decontamination Factor with variations in the blasting distance during three treatment durations for the decontamination of the inner surface of steam generator tubes [6]

Type of waste material that can be processed (input):

The process is most effective on flat surfaces made from durable material. Because the abrasive is sprayed, it can also be used on “hard to reach” areas. Application on aluminium or magnesium should be avoided due to the risk of dust explosions [2].

Secondary wastes

Secondary wastes from mechanical decontamination can include contaminated swarf or crud, fumes, aerosols and HEPA (High Efficiency Particulate Air) filters [1][4].

Recirculation of abrasives allows a significant reduction of the amount of secondary waste [2].

An example of the secondary wastes produced is presented below:

Table 2: Secondary wastes produced in the case of abrasive treatment [2]

Grit consumption	55 g/kg metal
Intervention clothing	5.3%
Grit waste	5.5%

References

- [1] A. Fuller (GSL), Surface Decontamination (Physical), Problematic Waste (PW) Toolkit
- [2] Nuclear Energy Agency Organisation for the Economic Co-operation and Development, NEA Task Group on Decontamination, Decontamination Techniques Used in Decommissioning Activities: <https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/decontec.pdf>
- [3] Rainbow Sandblasting & Spray Painting: <https://www.sandblasting-rainbow.com/> [accessed 04/24]
- [4] Environmental Protection Agency (USA) (2006), Technology Reference Guide for Radiologically Contaminated Surfaces, Office of Air and Radiation, Washington, DC 20460, EPA-402-R-06-003
- [5] FerroEcoBlast Europe, Dry Blasting: <https://ferroecoblast.com/technology/air-blasting/dry-blasting> [accessed 04/24]

[6] G.N. Kim et al. (2011), Abrasive Blasting Technology for Decontamination of the Inner Surface of Steam Generator Tubes, Nuclear Engineering and Technology, Vol.43 no.5

4.1.3 Dry ice blasting

Technology name: Dry ice blasting

Technology description

Dry ice blasting is a cleaning method that has proven to be very effective in removing contaminants and debris from various surfaces, including those found in the nuclear industry. This technique utilises solid carbon dioxide (CO₂) pellets, also known as dry ice, as the cleaning medium, which is propelled at high speeds to clean surfaces without causing any damage or leaving any residue. The process is entirely dry, meaning that it does not produce any secondary waste effluents. Dry ice blasting is also a non-toxic and environmentally friendly cleaning method that does not require the use of harsh chemicals or solvents [1].

Dry ice blasting is widely used in nuclear power plants to clean surfaces, equipment, and facilities contaminated with radioactive materials. It is particularly effective in cleaning heat exchangers, steam generators, reactor vessels, and other critical components of nuclear power plants [1]. Radioactive contaminants, from Class A to Class C, need to be removed and dry ice blasting is considered a safe, innovative process when removing oils, dirt, dust or paint from within the facility [2, 3].



Figure 1: Nuclear decontamination with CRYONOMIC dry ice cleaning machine [2]

Operating principles

The impact of pellets creates a Kinetic Energy Effect. The soft dry ice is accelerated by compressed air through specially designed nozzles at supersonic speeds. When the dry ice collides with the substrate being cleaned it creates a kinetic effect. Even at high impact velocities and direct head-on impact angles, the kinetic effect of solid CO₂ pellets is minimal when compared to other media (grit, sand). This is due to the relative softness of a solid CO₂ particle (1.5 – 2 on the Mohs Scale of Hardness), which is not as dense and hard as other projectile media. Also, the pellet changes phase from a solid to a gas almost instantaneously upon impact. The temperature of dry ice (-78.9°C) causes the contaminant to embrittle and the resulting micro-cracking helps break the bond between the surface and the contaminant. During the phase transition from solid to gas, the volume of dry ice expands up to 800 times in a few milliseconds and lifts the contaminant off the substrate. This is effectively a “micro-explosion” at the point of contact. The CO₂ gas expands outward along the surface and its resulting “explosion shock front” effectively provides an area of high pressure focused between the surface and the thermally-fractured contaminant particles, which carries the particles away from the surface [4]. Very little impact energy is transferred into the coating or substrate, so the dry ice cleaning process is considered to be non-abrasive.

<p>Technical maturity: TRL 9 – Technology and systems proven in an operational environment.</p>
<p>Limitations This process is mainly used to remove contaminated paint from metallic components. It is not an abrasive process. This process disperses contamination widely, which can cause problem with the ventilation and containment. It also increases the risk of asphyxiation if workers are exposed to the high CO₂ concentration atmosphere generated by the technique [5].</p>
<p>Secondary waste No secondary waste is generated, except in some cases HEPA filters [1, 2, 6]. Indeed, because of sublimation, of the dry ice, the radioactive contaminant remains in a dry, solid form during removal and containment. Additionally, the clean and decontaminated component can be released for reinstatement to use [6].</p>
<p>Decontamination efficiency It is possible to decontaminate tools, valves, and pumps, and to use the technique for cleaning and "free releasing" more fragile equipment, such as electric motors, instruments, gauges, precision tools and underwater television cameras [7]. No information was found regarding the decontamination efficiency.</p>
<p>References [1] CMW CO₂ Technologies: https://cmw-dryice.com/industry/nuclear-decontamination [accessed 06/24] [2] Cryonimic Dry Ice Cleaning Solutions: https://www.cryonimic.com/en/applications/1293/dry-ice-blasting-for-power-generation/nuclear-decontamination-in-npp [accessed 06/24] [3] Optimum Dry Ice Blasting: https://optimumdryiceblasting.co.uk/dry-ice-blasting-services/nuclear-decommissioning-decontamination-services/ [accessed 06/24] [4] How does dry ice blasting work?: https://blog.coldjet.com/how-does-dry-ice-blasting-work [accessed 06/24] [5] M. Tachon, CEA Marcoule, Techniques et procédés appliqués au démantèlement, DEN/DPAD/MT [6] World Intellectual Property Organization, IPO/PCT, Patent: Cleaning of radioactive contamination using dry ice, WO 2014/031179, PCT/US2013/032900 [7] P.J. Gillis et al, Decontamination and recovery of materials at nuclear facilities - operating history, CANDU maintenance conference 1995, CA9800508</p>

4.1.4 Laser decontamination technologies

Laser decontamination is a surface cleaning technique that employs high-powered lasers to remove layers of contamination. The technique is under active development and a range of different laser types and operating procedures are being tested at different facilities. This section provides a summary of the general principles, applicability and limitations of this technique and three specific laser decontamination technology examples, which are currently under development.

<p>Technology name: Laser decontamination</p> <p>Technology description</p> <p>Laser decontamination is a surface removal technology of contaminated metal components and equipment of reactors, reprocessing plants and accelerators via laser so as to reach free release levels or possible recycling/reuse in low-level radioactive metal facilities [1].</p> <p>The main types of lasers used in laser decontamination research include CO₂ lasers, fibre lasers and excimer lasers. However, fibre lasers are now preferred in laser decontamination technology due to their high coupling efficiency, high conversion efficiency and good beam quality [1].</p> <p>Interaction of laser with the substance during laser decontamination includes complex mixture of various physical and chemical effects. During the irradiation of material surfaces via laser beam, there will be heating, melting and vaporisation in the local microregion, in the meantime, the metal vapor is heated further and ionised by the laser to form plasma above the molten pool [1].</p> <p>Operating principles</p> <p>The beam emitted by the laser system passes through the collimating lens for beam shaping, then the shaped beam enters the galvanometer scanner through the mirror. The specimen surface is moved to the focal position of the focusing lens by adjusting the height of the laser head. The laser spot is applied orderly to the simulated specimens by swinging the x- and y-axis mirrors in the galvanometer system, thereby achieving decontamination. In order to prevent the escape of aerosol which can contaminate the environment, the laser decontamination should be carried out in an acrylic sealed box or a stainless-steel sealed chamber. The contaminated specimen is mounted in a sealed chamber. Vacuum pump is connected to the sealed box to ensure that the pressure of the box is below atmospheric pressure. Meanwhile, a high efficiency filter is installed at one end of the sealed box for collection of radioactive aerosol particles and to avoid contaminating the vacuum pump equipment [1].</p> <p>Technical maturity:</p> <p>TRL 7 – Recently proven technology (system prototype demonstrated in an operational environment).</p> <p>Limitations</p> <p>Laser treatment can effectively remove the radioactive contaminants from the metals' surface, however, it will also influence the surface properties of the metal substrate. Microstructure and composition of laser decontaminated surfaces are essential parameters affecting the corrosion resistance. Therefore, it is particularly significant to study the thickness, composition and structure of the oxide layer on the metal surface.</p> <p>The parameters for laser decontamination are variable and difficult to match. Various parameters that affect laser decontamination qualities include laser fluence, spot overlap rate, laser irradiation times, irradiation angles and pulse duration [1].</p> <p>The technique is more effective for treating items of waste with simple planar geometries. Unexposed surfaces cannot usually be decontaminated as the equipment needs to be able to enter the decontamination area. The size of the object to be decontaminated will be dependent to the equipment.</p>
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Secondary waste

Contaminated particles ablated from the surface are captured on HEPA filters which will concentrate the activity and so it is important to know how to treat them [2]. The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment.

The concentration and size distribution of aerosol generated during the laser decontamination process are influenced by laser wavelength, pulse duration and laser fluence. Laser ablation results in the generation of two main structures for aerosols: spherical nanoparticles and chain structures formed by agglomeration of nanoparticles. Cooling rate affects the size and concentration of nanoscale particles, a faster cooling rate results in smaller sizes of aerosol particles. The chain structure is composed of dozens or even hundreds of nanoparticle aggregates formed by collision and coalescence [1].

Decontamination efficiency

In terms of removal of fixed contaminants, the decontamination factor could be more than 15, whereas it can be greater than 100 for loose contaminants [1].

References

- [1] Q. Wang et al (2023) Laser decontamination for radioactive contaminated metal surface: A review, Nuclear Engineering and Technology, 55, 12-25
- [2] K. H. Leong, B. V. Hunter, J. E. Grace, M. J. Pellin, H. F. Leidich, and T. R. Kugler (1996) Laser-based characterization and decontamination of contaminated facilities, International Congress on Applications of Lasers & Electro-Optics 1996, A85-A94

4.1.4.1 Ames-LMIT Laser Decontamination Experimental Solution

Technology name: A Laser-Based Solution to Industrial Decontamination Problems**Technology description**

The Ames Laboratory and Lockheed Martin Idaho Technology (Ames-LMIT) developed laser technology to remove contaminants that are embedded within the metal surface [1]. The bench-top system (shown in Figure 1) uses a high-power Nd:YAG laser to remove microns of metal from a surface. A vacuum off-gas system prevents the redeposition of materials removed from the surface. Metal samples were mounted on a computer-controlled X-Y translational table and moved beneath the stationary laser beam at a maximum speed of 10 cm/s.

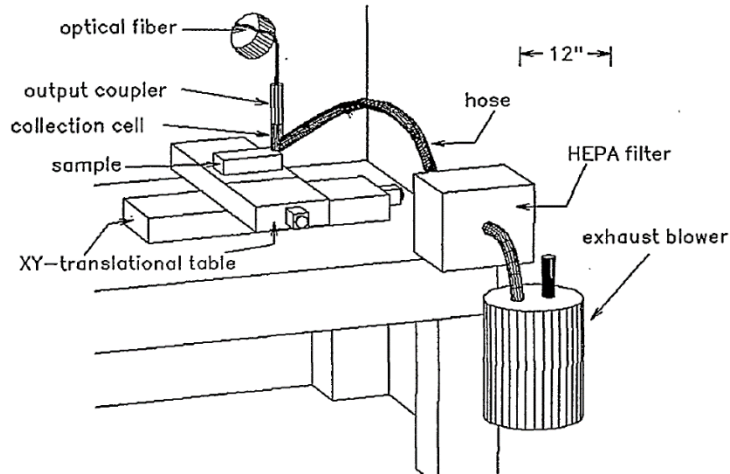


Figure 1: Expanded view of the experimental setup for laser ablation [1].

Technical maturity:

TRL 4 – Lab-validated technology.

Types of metals treated (including limitations on size and activity)

The system has been tested on two metal types, stainless steel and lead, that were artificially contaminated with radioactive Zr and Cs. This equipment is currently operating at the bench scale and has only been tested with flat sheets of metal, no larger than 10 x 20 cm [1].

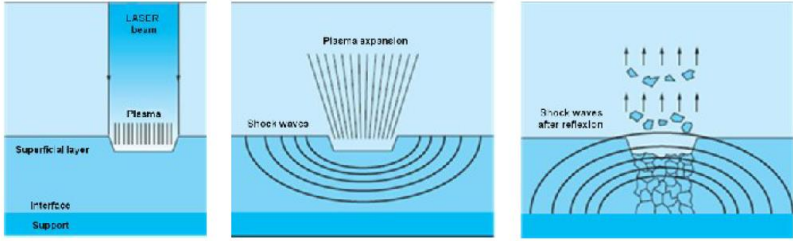
Product characteristics (including decontamination efficiency)

In tests with the stainless steel, after two passes under the laser over 95% of Zr and nearly 100% of Cs was removed [1].

References

[1] M.C. Edelson, Ho-Ming Pang, and Russell L. Ferguson (1995) A laser-based solution to industrial decontamination problems, International Congress on Applications of Lasers & Electro-Optics 1995, 768-777

4.1.4.2 Areva-CEA Laser Ablation Process

<p>Technology name: Surface Decontamination Using Laser Ablation Process</p> <p>Technology description</p> <p>A new decontamination method was investigated and used during two demonstration stages by AREVA (now Orano/Framatome), in collaboration with CEA. This new method is based on the use of a laser beam to remove the contaminants present on a base metal surface. Experiments were carried out using the Nd:YAG (neodymium-doped Yttrium Aluminium Garnet) laser technology. The laser decontamination technique works by rapidly heating the surface layer of the metal. When the temperature of the metal is increased sufficiently it forms a plasma, which expands and produces microscopic cracks in the metal surface causing the ejection of contaminated particles.</p> <p>Two different lasers were used during the experiments [1]:</p> <ul style="list-style-type: none"> • The first one was optically pumped with flash lamps and with a power of 36 watts. • The second one was also optically pumped but with diodes; the power of this second equipment was 300 watts. <p>The laser decontamination equipment is placed in a sealed hot cell and hand-held by an operator to reduce secondary contamination hand-handled [1] or potentially remote-handled (e.g. [2]).</p>  <p style="text-align: center;"><i>Figure 1: Ablation laser principle</i></p>
<p>Technical maturity:</p> <p>TRL 7 – Prototype demonstration in operational environment at system level.</p>
<p>Types of metals treated (including limitations on size and activity)</p> <p>The laser ablation technology can be used to treat a wide range of contaminated metals including stainless steel and carbon steel plates and lead ingots, covered with different types of contamination such as paint, metallic oxides, radionuclides and grease [3, 4].</p> <p>The system has been tested with a wide range of different items, up to a few metres in size. The main limitation on size is the time required for treatment and the dimensions of the treatment hot-cell (if utilised) [3].</p>
<p>Product characteristics (including decontamination efficiency)</p> <p>Although several treatments were required, the laser decontamination technique trialled at CEA was able to remove up to 100% of the decontamination, confirmed by electron microscopy [1, 3].</p> <p>Experiments using metal pieces from La Hague showed decontamination factors of 100 for α, and 50 for $\beta\gamma$, after five minutes of laser ablation.</p>
<p>References</p> <p>[1] F. Moggia, F.X. Lecardonnel and F. Damerval. (2012) Surface Decontamination Using LASER Ablation Process - 12032, WM Symposia, 1628 E. Southern Avenue, Suite 9-332, Tempe, AZ 85282 (United States), 26 Feb - 1 Mar 2012</p> <p>[2] IPG Photonics, https://lasersystems.ipgphotonics.com/products/robotic-workstations/Ablation-LaserCell, [accessed 07/24]</p>

- [3] F. Moggia, L. Objois, V. Toulemonde, (2014) LASER decontamination of metallic, Symposium on Recycling of metals arising from operation and decommissioning of nuclear facilities, April 8-10, 2014 Nyköping (Sweden)
- [4] V. Blanc, F. Moggia and H-N. Guerif (2015). Technologies applying to D&D, GLOBAL 2015 conference (Paris), Paper 5C3-1, September 2015

4.1.4.3 LaPLUS Laser-based decontamination technique

Technology name: Laser-based decontamination of metal surfaces

Technology description
 A test was undertaken to remove epoxy paint from the surface of metal (ferritic steel and austenitic steel) using a pulsed 150W Nd:YAG laser. To simulate surface contamination, radionuclides relevant to decommissioning, such as Co-60, Cs-137 and Sr-90, were substituted using their stable isotopes [1]. Figure 1 shows a schematic of the experimental set up.

Figure 1: Schematic of laser ablation test set-up [1].

Laser treatment was executed using laser fluence of 4.38 J/cm² and an applied energy per surface area of either 115 J/cm² or 460 J/cm².

Technical maturity:
 TRL 4 – Starting to be developed in a laboratory or a research facility.

Types of metals treated (including limitations on size and activity)
 The tested materials were small pieces of ferritic steel and austenitic steel, with dimensions 100 mm x 50 mm x 2 mm.

Product characteristics (including decontamination efficiency)
 The laser treatment significantly reduced the amounts of surface contamination. Specific decontamination factors for different elements are shown in Table 1.

Table 1: Concentration of surrogates before and after decontamination and respective decontamination factors [1].

Element	Sr	Cs	Co
Concentration before decontamination	0.37 – 0.38%	2.8 – 3.1%	0.66 – 0.72%
Concentration after decontamination	0.002 – 0.015%	0.03 – 0.04%	0.21 – 0.72%
Decontamination factor	96%	98.7%	62%

Increased laser fluence leads to faster removal rates, while short pulses minimise changes of the metals grain structure. Optimisation of the processing parameters enabled the selective removal of the decontamination paint without any heat impact to the metallic substrates [1].

References

[1] G. Greifzu, et al. (2019), Laser-based decontamination of metal surfaces, Optics & Laser Technology, Volume 117, Pages 293-298,
<https://doi.org/10.1016/j.optlastec.2019.04.037>

4.2 Chemical decontamination techniques

Many chemical decontamination techniques can be used to decontaminate metallic wastefoams such as chemical bath, electrochemical decontamination, Chemical Oxidation Reduction Decontamination (CORD), Chemical Oxidation Reduction using nitric permanganate and oxalic acid MIXture (COREMIX-HP), Metal Decontamination by Oxidation with Cerium (MEDOC), decontamination gels (Aspigel and Electrolytically Assisted Surface Decontamination (EASD) gels) and decontamination foams, whose datasheets are presented below. It has to be noted that it is also possible to use pressure jet washing (Section 4.1.1) with a chemical solution for decontamination [9].

4.2.1 Chemical baths

Technology name: Chemical baths

Technology description

Surface contamination can be removed from metals by submerging them in a chemical wash (tank immersion for example, Figure 1). Various decontamination chemicals can be used including detergents, dilute acids/bases and organic complexing agents. The aggressiveness of the washing chemicals (e.g. the strength of acid used) can be varied depending on the depth of the contamination present. Contamination that has penetrated the surface layers of the metal may require these layers to be dissolved and removed by, for example, submerging the metal in a bath of strong acid or base, as shown in the figure below.



Figure 1: Before (left) and after (right) images of stainless steel being decontaminated in an acid bath [1].

The chemical bath technique can be enhanced by ultrasonically agitating the liquid in which the material is placed. This combines physical as well as chemical actions to further remove material from the surface [1]. The bath can also be heated to accelerate the cleaning process.

Operating principles

For example, we can have a two-stage process. In this case, alkaline permanganate solutions are the most common reagents used at the first stage. At the second stage a variety of reagents such as ammonium citrate, ammonium citrate followed by EDTA, oxalic acid, a mixture of citric and oxalic acid, sulphuric acid, etc., have been used successfully for various applications for the decontamination of stainless steel, carbon steel, inconel, zircaloy cladding, etc. Sulphuric, phosphoric, hydrochloric, hydrofluoric acids and other reagents have been successfully used separately as individual aggressive decontaminants, generally at concentrations from 2 to 15 per cent. The process may need to be repeated several times to achieve the required decontamination level. Care must be taken if the dissolution process might result in unacceptable surface corrosion, e.g., where direct reuse of an item is required [2].

Technical maturity:

TRL 9 – Technology and systems proven in an operational environment.

Types of metals treated (including limitations on size and activity)

The technique can treat a wide range of metals that have surface contamination. If submersion is required, then the dimensions of the acid bath will place a limit on the dimensions of the metal items that can be treated (without size reduction). The technique is only suitable for treating metal that is surface contaminated. Metals containing bulk contamination or activated metals will not be effectively treated by this process.

This decontamination technique is not suited to the treatment of wastes with complex geometries and poorly exposed or inaccessible surfaces. Only the surface in contact with the solution will be treated [2].

Because the tanks are usually open at the top, a proper ventilation system must be installed, and special care must be taken to avoid contact between the operators and the highly corrosive reagents. It should be noted that chemical reagents at excessively high temperatures may result in undesirable effects, such as generation of toxic or explosive gases, e.g. hydrogen [2].

Product characteristics (including decontamination efficiency)

The technique will remove surface contamination, leaving metal that is either free from contamination or that has greatly reduced levels of associated radioactivity.

Secondary wastes

Surface cleaning techniques can often result in large volumes of liquid chemical secondary waste which are radioactively contaminated and will require neutralisation/effluent treatment, including filtering if required to remove metal particles. Chemical decontamination requires efficient recycling of reactive chemicals, as insufficient recycling of decontamination reagents may increase the amount of secondary waste. This technique may generate mixed waste which may be difficult to treat, and it may result in corrosion and safety problems when misapplied [2]. The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment.

Some decontaminants (e.g. complexing agents such as EDTA) may render the secondary waste unsuitable for disposal at some disposal facilities, e.g. the LLWR in the UK [2].

References

- [1] IAEA (2006) Decommissioning of Nuclear Facilities: Decontamination Technologies
- [2] NEA Task Group on Decontamination, Decontamination Techniques Used in Decommissioning Activities: <https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/decontec.pdf>

4.2.2 Electrochemical decontamination

<p>Technology name: Electrochemical decontamination</p> <p>Technology description</p> <p>Electrochemical treatments are based on the principles of electrolysis, which involves passing a direct current through an ionic substance (the electrolyte) from one electrode (the anode) to another (the cathode). The process can be used to remove surface contamination from metal components. Some specific examples are presented below. To treat the contaminated metal (that acts as the anode), it is placed in a bath of electrolyte and a current is applied. This causes the contaminated surface layer of the metal to dissolve and the charged ions (including the contaminants) to be removed to the cathode.</p> <p>Operating principles</p> <p>Electrochemical decontamination uses direct electric current, which results in the anodic dissolution and removal of metal and oxide layers from the component. The dissolution may be conducted by immersing items to be decontaminated in an electrolyte bath as anode or fitted with anodes. This method is useful for decontaminating items with easily-accessible surfaces. Current may also be delivered to a submerged component by moving a pad over the surface to be decontaminated, as an efficient method for regular surfaces. The electrolyte is continuously regenerated by recirculation. For in-tank electropolishing, at least two (stainless steel) tanks are required. One tank contains the electrolyte, electrodes, and parts to be decontaminated. The other tank holds the water used for rinsing the parts after decontamination. Electrical currents of up to 2,700 A are common.</p> <p>To control vapours released from the electrolyte during the electropolishing process, an extraction hood is located alongside the electropolishing tank. Provisions for heating and agitating the electrolyte as well as rinsing the tank are also required. Electrochemical decontamination is effective and gives a high decontamination factor. Important operating parameters for electrochemical decontamination are electrolyte concentration, operating temperature, electrode potential and current density. The effectiveness of the decontamination may be limited by the presence of adhering materials on the surface of the items to be decontaminated.</p> <p>Phosphoric acid is normally used as the electrolyte in electropolishing because of its stability, safety and applicability to a variety of alloy systems. Moreover, the non-drying nature of phosphoric acid helps minimise airborne contamination, and the good complexing characteristics of phosphoric acid for metal ions is a significant factor in minimising recontamination from the electrolyte.</p> <p>Other electrolytes, such as nitric acid and sodium sulphate have been investigated and proposed as alternatives to phosphoric and sulphuric acid. The need for new electrolytes was initially motivated by the incompatibility of phosphoric and sulphuric acids with existing treatment facilities and the possibility of producing secondary liquid waste which is easier to process or regenerate [1].</p>
<p>Technical maturity: TRL 5 – Pilot scale (validation in relevant environment) [3].</p>
<p>Types of metals treated (including limitations on size and activity)</p> <p>Electrochemical decontamination processes may only be applied for removing radionuclide contamination from conducting surfaces, such as iron-based alloys (including stainless steel), copper, aluminium, lead and molybdenum. Materials such as oil, grease, oxides (rust) and paint or other coatings should be removed before decontamination [1]. The size of items that can be treated will be limited only by the dimensions of the electrolyte bath in which they must be submerged.</p> <p>The technique is only suitable for treating metal with surface contamination.</p> <p>The use of electrochemical decontamination is limited: when immersion is used, by the size of the bath, and when a pad is used, by the geometry of the surfaces and the available free space around</p>

the part being treated. This makes the method almost inapplicable for industrial decontamination of complex geometries (e.g., small-diameter pipes) [1].

Electrochemical decontamination causes a steady increase of dissolved iron in the phosphoric acid (when used). If the iron content exceeds 100 g/dm³, a precipitation of iron phosphate occurs and prevents the decontamination process. Therefore, the acid must be exchanged or regenerated periodically. In doing so, the volume of effluents is limited; however, handling the parts to be immersed or the pad, may lead to additional exposure to workers [2].

Product characteristics (including decontamination efficiency)

The process will produce fully decontaminated metal that is free of surface contaminants that may be suitable for re-use or free release as scrap.

The reduction in ⁶⁰Co activity by a factor of 2–10 and ¹³⁷Cs activity by a factor of 7–100 was achieved [2].

Secondary wastes

The process will lead to the contamination of the cathode, which will become secondary waste. The decontamination technique may concentrate contaminants from a large number of metallic items into a single cathode. Therefore, the secondary waste is likely to have higher specific activity than the untreated metal, but it will represent a much smaller volume.

The electrolyte used in the process will also become secondary waste. Off-gasses are produced, including CO₂ and CO.

The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment.

References

- [1] NEA Task Group on Decontamination (1999), Decontamination Techniques Used in Decommissioning Activities, <https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/decontec.pdf>
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4.2.3 CORD

Technology name: Chemical Oxidation Reduction Decontamination (CORD)**Technology description**

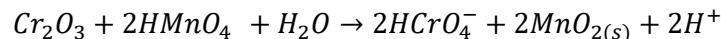
CORD is a 4-step regenerative decontamination process, which uses oxidation and reduction to dissolve the oxide film from a carbon/stainless steel metal surface, while capturing the radionuclides in ion exchange resins. It can also attack the base metal in function of the chosen parameters. The technique can be used in-situ for maintenance of the reactor (cleaning the primary circuit) or post-operational clean out. The first step, which is the oxidation step, involves attacking the chromium oxide layer (oxidation of Cr III in Cr IV in an acid (NP CORD) or alkaline medium (AP CORD)) using the permanganate ion (MnO_4^-). In NP CORD, permanganate acid is used ($HMnO_4$), while potassium permanganate is used in AP CORD [1]. The NP media is preferred when the amount of chromium is higher than 30%.

1. Step 1: pre-oxidation - dissolution of chromium oxide.

This step usually takes from three to six hours.

a. NP CORD

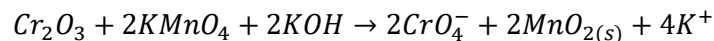
The permanganate ion oxidises the chromium oxide according to the reaction below. This step is carried out at a concentration of 2.5 mM of permanganate ion and about 3 mM concentration of nitric acid in the case of NP CORD. This stage is operated from 80°C to 110°C for about three hours. [1-2]:



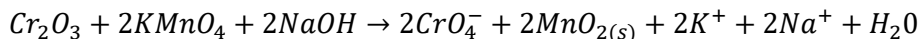
It leads to the production of manganese oxide in the systems. The acidic media can also attack the iron oxide.

b. AP CORD

AP CORD is realised with potassium permanganate and sodium hydroxide or potassium hydroxide.



Or



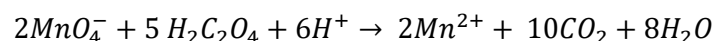
This can clog the ion exchange resins and therefore, the ion exchange resins are disconnected from the system during this stage. This step has the following impacts on the system:

- Reduction in the kinetic release in the Cr(VI) decontamination solution.
- Low increase of the concentration of chromate ions in this solution (2-3% in one hour).

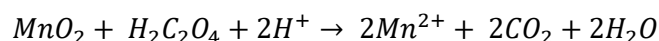
2. Step 2: reduction of the oxidation solution

Neutralisation of the surplus solution produced in step 1 is realised by reduction with stoichiometric amounts of oxalic acid (reduction of Mn (VII) in Mn (II) and elimination of the manganese layer formed in the previous step).

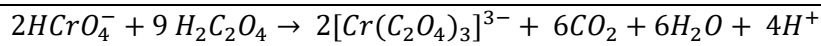
The oxalic acid therefore dissolves the manganese oxide to give manganese ions (Mn^{2+}) in the system



Reduction of MnO_2 :



Reduction of Cr(VI) in Cr(III) and complexation with excess of oxalic acid.

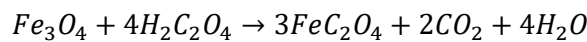


This complex is not retained on the resins and will be present during the whole decontamination.

3. Step 3: decontamination

- Elimination of Mn^{2+} ions and the corrosion products by the ion exchange resins (in the case of AP CORD, the amount of resins will be higher because of the presence of Na^+ or K^+).
- The monitoring of this step is done by following the decrease of the activity and the concentration of the corrosion products of the oxide layer.
- The dissolution of the metal oxide (Fe_3O_4 , $Fe_2O_3...$) and of base metal (when wanted) is realised with the excess of oxalic acid

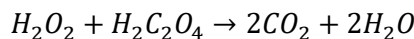
The dissolution of magnetite by oxalic acid is as follows:



This step is usually operated at about 80°C or more and lasts for four/five hours. These iron and nickel ions can then be captured by the ion exchange resins.

4. Step 4: decomposition of the oxalic acid in the form of water and CO_2 with the use of UV and hydrogen peroxide

The decomposition is realised by the photocatalytic oxidation in wet process by using UV, hydrogen, peroxide and Fe (III) as a catalyser (Fenton reaction):



The CO_2 is vented out and can be captured leaving only metal ions to be captured by the ion exchange resins. The oxalic acid could also be destroyed using anion exchange resins which results in decreased amounts of resins required, and thus of secondary waste. [1]

- Monitoring of the oxalic acid, iron and hydrogen peroxide concentrations
- Monitoring of the decrease of the activity of the solution

Use of the resins. When step 4 is finished, the solution is recycled for use in a new cycle. All along the cycles, the solution is treated in a closed loop on resins and no transition step has to be done between the pre-oxidation and the decontamination.

A typical CORD cycle takes 10 to 36 hours [1].

A simple summary of HP CORD is shown below.

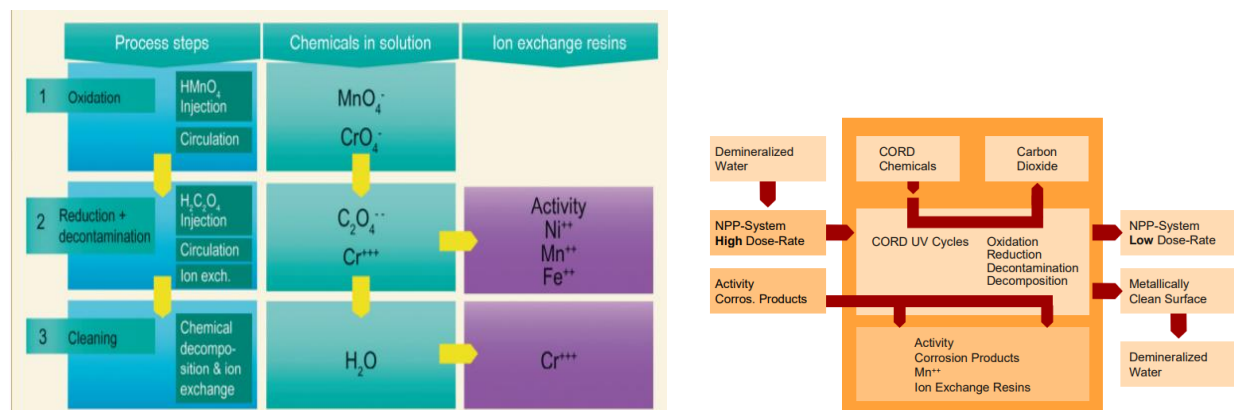


Figure 1: Illustration of the multistage CORD process. Redrawn and modified from original AREVA [2,4]

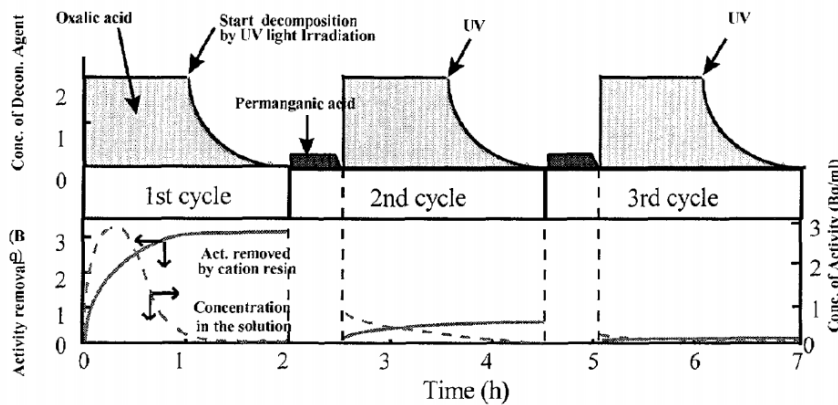


Figure 2: Decontamination profile of CORD-UV [3]

A variation of CORD, known as CORD D UV (to attack base metal), where D stands for decommissioning, makes use of UV in the decontamination stage along with an increase in concentration of oxalic acid, which leads to a change in redox potential from +100mV to -275mV (versus Ag/AgCl). This increases the efficiency of the decontamination step, yielding higher decontamination factors. [1]

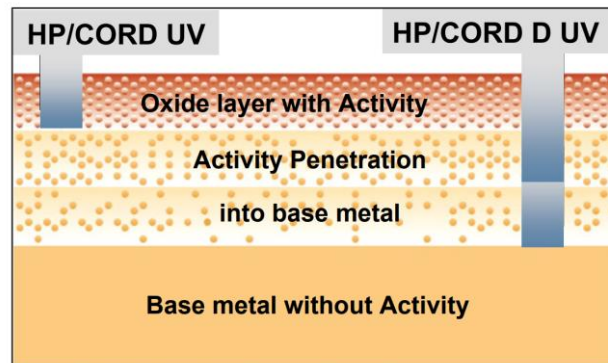


Figure 3: Comparison between HP/CORD UV and HP/CORD D UV [5]

Technical maturity:

TRL9 – Proven technology

Types of metals treated (including limitations on size and activity)

The CORD method can be applied to all types of metallic waste from nuclear power plants. It is compatible with carbon steel which is used in BWR plants and with stainless steel and Ni-alloys which are used in PWR plants. During maintenance, this technique can be utilised to decontaminate the system without the need to defuel the reactor, which leads to lower levels of recontamination. [1]

Product characteristics (including decontamination efficiency)

For HP CORD, three chemicals are required to be brought to site for decontamination which are permanganic acid (2-4 wt% aqueous solution), oxalic acid dihydrate (solid), and hydrogen peroxide (30-50 wt% aqueous solution). For some applications solid potassium permanganate is brought to site from which permanganic acid is produced in a separate module prior to addition to the system. [1] For NP CORD, potassium permanganate and nitric acid are required. The decontamination factors can range from 10 to 100 depending on the number of cycles implemented. After treatment with CORD, ion exchange resins are produced alongside pure water and captured CO₂. The resins capture most of the radionuclides. The decontaminated metal could be reclassified from intermediate level waste (ILW) to low-level waste (LLW) or very low-level waste (VLLW). As an example, the decontamination factors achieved for steam generators in an operational context by Areva are as follows (Table 1):

Table 1: Full System Decontamination summary [6]

Activity & Corrosion products removed	NPP Unterweser (KKU)	NOO Neckarwestheim-1 (GKN1)
Corrosion products (Fe, Cr, Ni)	459 kg	260 kg
Total activity removed (>99% Co-60)	9.1E+13 Bq (2,460 Ci)	1.1E+13 Bq (297 Ci)
Decontamination Factors (DF) achieved		
DF overall	94.5 (83 MP)	81 (66 MP)
DF primary circuit (Loop & PZR)	158 (26 MP)	31 (20 MP)
DR SG tubing area	147 (16 MP)	224(MP)
DF auxiliary systems (RHR/CVCS)	35 (41 MP)	44 (31 MP)
Waste		
Ion Exchange Resins	21 m ³ (planned 23 m ³)	11 m ³ (planned 15 m ³)

*MP: measuring point

Some data regarding the decontamination efficiencies achieved in different reactors are presented in Table 2 [2,4].

Table 2: CORD Decontamination efficiency

Country	Nuclear power plant	Year	Type of reactor	Decontamination Factor (DF)
USA	Connecticut Yankee	1998	PWR 619 MWe	16
Sweden	Oskarshamn 1	1994	BWR 442 MWe	20 to 1000
Finland	Loviisa 2	1994	VVER 445 MWe	14 to 153
Japan	Fukushima 3	1997	BWR 760 MWe	43 to 72
Japan	Fukushima 2	1998	BWR 760 MWe	68 to 108
Japan	Fukushima 5	2000	BWR 760 MWe	35 to 83

Secondary wastes

The secondary waste issued from the process are:

- Chemical solutions, noting that the volume of the chemical solution is at least equal to the volume of the decontamination loop.
- Water used for the treatment of the resins.
- CO₂.

The waste issued from the effluent treatment are [2]:

- Active resins.
- Filters.
- Technological waste.
- Other waste such as tools, hoses, valves, etc.

More precisely as an example for the treatment of a steam generator, the secondary waste produced were [7]:


- Ion Exchange Resins :
 - 27 m³ for oxide layer and secondary waste (99+% of activity).
 - 10 m³ for base metal removal (<1% of activity).
 - 1 m³ for waste water treatment.

- Waste Water Treatment:
 - Alpha contamination removal from process water prior to disposal.
 - Total of 95 m³ waste water successfully treated.
 - Target < 1 Bq/L alpha.
- Bag Filters: Total of 16 bag filters were used to collect solids.

References

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- [6] C. Topf *et al.*, Areva (2016), Full System Decontamination Prior to Decommissioning - Comparison of Decontaminations Performed at PWRs Unterweser & Neckarwestheim 1 and BWR ISAR 1
- [7] L.S. Belda, Areva, Decontamination of the 4 steam generators, the pressurizer and loop piping at the French NPP Chooz A

4.2.4 COREMIX

Technology name: Chemical Oxidation REDuction using nitric permanganate and oxalic acid MIXture (COREMIX-HP) 

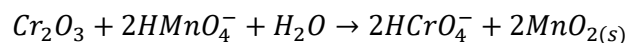
Technology description

COREMIX is a 2-step regenerative decontamination process, which is a simplified version of the existing CORD process. COREMIX uses sequential oxidation and reduction to dissolve the oxide film from a stainless steel and Ni-alloy metal surface, while capturing the radionuclides in ion exchange resins. It can also attack the base metal in function of the chosen parameters.

The technique can be used in-situ for maintenance of the reactor (cleaning the primary circuit) or post-operational clean out. The first step, which is the oxidation step, involves attacking the chromium oxide layer (oxidation of Cr(III) in Cr(IV) in an acid (referred to as nitric permanganate (NP)) using the permanganate ion (MnO_4^-). In the second step, which is the reduction step, oxalic acid is added to reduce the permanganate ion to Mn^{2+} ions and to dissolve the iron and nickel enriched oxide layer from the contaminated surface of the metal [1]. These steps can be repeated multiple times until the target level of decontamination is reached.

1. Step 1: Pre-oxidation - dissolution of chromium oxide.

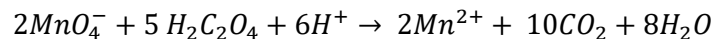
This step usually takes three hours to complete. The permanganate ion oxidises the chromium oxide according to the reaction below. This step is carried out at a concentration of 15 mM of potassium permanganate and about 3 mM concentration of nitric acid. This stage is operated at 80°C for about three hours. [1-3]



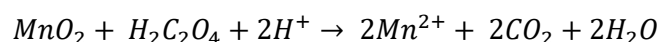
It leads to production of manganese oxide in the systems. The acidic media can also attack the iron oxide.

2. Step 2: Reduction and dissolution of iron and nickel oxide

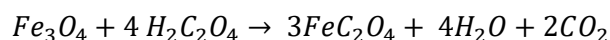
Oxalic acid is added to reduce the remaining $KMnO_4$ to Mn^{2+} according to the following equation;



The oxalic acid also dissolves the MnO_2 precipitate that is formed in the previous step. A total of 1.7 times the concentration of $Kmno_4$ is utilised in this step.



Excess oxalic acid (18.5 mM) is added to perform the decontamination reaction that involves the dissolution of Fe_3O_4 according to equation,



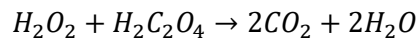
The reduction and dissolution are combined and applied at 80°C for a total of three hours. These steps comprise of one cycle of the process. Multiple cycles of the process can be applied to reach the target level of decontamination. No additional rinsing or cleanup is required in between the steps or in between two cycles. A typical COREMIX cycle takes six hours [1].

3. Cleanup step using decomposition of the oxalic acid with the use of hydrogen peroxide.

Oxalic acid is present in excess in the effluent from the COREMIX process and must be destroyed prior to any other treatment process. It is a very strong chelating agent that can cause problems during the waste conditioning stage and its presence is therefore highly undesirable.

Decomposition is realised by the disproportionation process, using hydrogen peroxide to generate CO_2 and H_2O . This reaction is catalysed by the presence of cationic metals, such as Mn^{2+} or Fe^{2+} (Fenton reaction). This reaction is performed at 80°C for a 24h period under agitation after addition of 0.1 M of hydrogen peroxide. The inclusion of this step leads to a process called COREMIX-H

(Chemical Oxidation REduction using nitric permanganate and oxalic acid MIXture with Hydrogen peroxide treatment).



The CO_2 is vented out and can be captured leaving only metal ions to be treated using ion exchange resins or a precipitation process.

A summary of the COREMIX process is shown below (Figure 1).

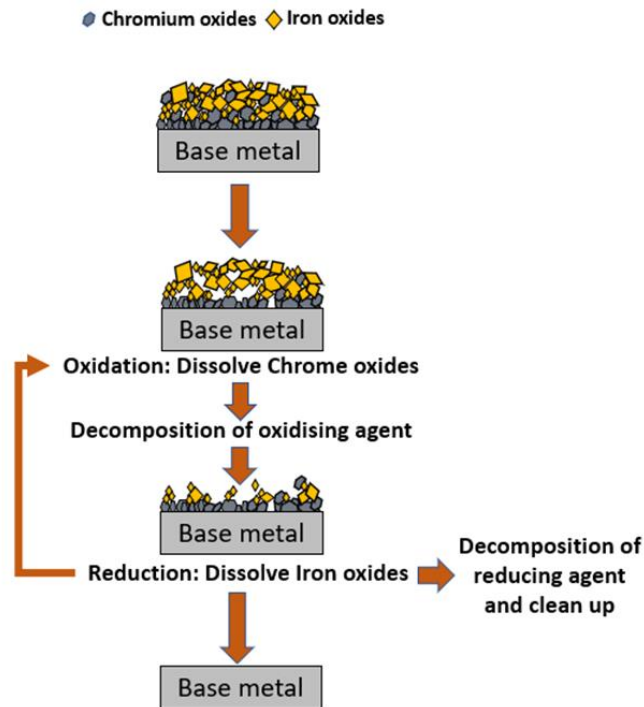
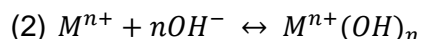
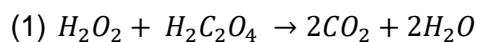


Figure 1: Operating principle of the COREMIX process, modified from Hitachi-GE Nuclear Energy, Ltd.'s [4], description of the CORD process, which follows a similar chemistry.

While ion exchange resins are typically used to decontaminate the CORD effluents, a precipitation protocol following the COREMIX process was developed during the PREDIS project (Figure 2).

4. Precipitation of radionuclides and metals in solution as hydroxide sludge

Following decontamination, effluent treatment involves destruction of the oxalic acid (equation 1) and then a 2-step alkaline precipitation at pH 8.5 (Cr, Ce, Fe, Zn precipitation) and pH 12 (Ni, Mn Co, Ag precipitation) to produce radioactive sludge (equation 2) and a decontaminated solution [1].



Each precipitation step is followed by a filtration step to collect the resulting sludge, thus avoiding the re-solubilisation of the metals when the pH is modified. This step reduces the amount of metals by 29% after the first precipitation at pH 8.5 and by about 100% after the second precipitation at pH 12. Moreover, the sludge produced during the process can be dried in order to provide suitable storage conditions.

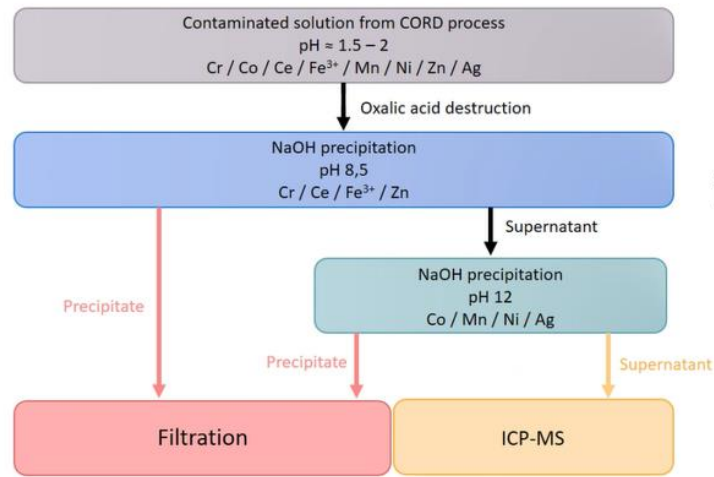


Figure 2: Two-stage precipitation protocol for decontamination of CORD (now COREMIX) liquid effluents [1]

As this stage follows on from the COREMIX-H protocol, it has been named COREMIX-HP (Chemical Oxidation Reduction using nitric permanganate and oxalic acid MIXture with Hydrogen peroxide treatment and Precipitation).

This stage has been optimised for hydroxide precipitation, but further tests with other types of precipitants (phosphate, sulphide, and electrocoagulation) are underway to optimise the technique to the different metals and radionuclides present in solution.

Technical maturity:

TRL 2-3 – Proven in laboratory tests

Types of metals treated (including limitations on size and activity)

The COREMIX-HP method can be applied to all types of metallic waste from nuclear power plants. It is compatible with carbon steel which is used in BWR plants and with stainless steel and Ni-alloys which are used in PWR plants. During maintenance, this technique can be utilised to decontaminate the system without the need to defuel the reactor, which leads to lower levels of recontamination. [1]

Product characteristics (including decontamination efficiency)

For COREMIX-HP, the following chemicals are required to be brought to site for decontamination: potassium permanganate (solid); nitric acid (70%); oxalic acid dihydrate (solid); hydrogen peroxide (30-50 wt% aqueous solution); and sodium hydroxide (solid).

A decontamination factor of around 2.5 was attained after 5 cycles when applied to Ni-alloy samples in the laboratory setting. Further cycles were not applied to limit dose exposure as, in a laboratory setting, the samples required almost direct handling. A decontamination percentage of ~70% was achieved following 5 cycles (36 hours treatment time). As the contaminated effluent from the COREMIX process is treated by precipitation, no waste is produced at the end of this stage, except CO₂. The decontaminated metal could be reclassified from intermediate level waste (ILW) to low-level waste (LLW) or very low-level waste (VLLW). As in the case of liquid effluent treatment, the precipitation process produces solid waste such as contaminated filters and sludge.

The subsequent precipitation step, for ⁶⁰Co (which was the main contributor), the final activity of the liquid samples was around 5 Bq/L as compared to an initial activity of around 15.8 kBq/L, leading to a decontamination factor around 3000.

Table 1: Decontamination efficiency of the COREMIX-HP process

Coupon material	Comments	Mass loss	Area treated (cm ²)	Removal (mg/cm ²)
304L	V/S 0.4 m, 3 cycles	6.86 mg	7.53	0.91
304L	V/S 0.18 m, 3 cycles	8.8 mg	8.13	0.96
316Ti		6.71 mg	1	6.71

Secondary wastes

The secondary waste arising from the COREMIX process are:

- The volume of the chemical solution after each cycle is at least equal to the volume of the decontamination loop.
- CO₂.

The waste issued from the effluent treatment are:

- Filters
- Technological waste
- Other waste such as tools, hoses, valves... [3]

References

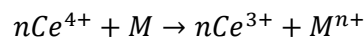
- [1] Rivonkar, A et al. (2022), Optimisation of the chemical oxidation reduction process (cord) on surrogate stainless steel in regards to its efficiency and secondary wastes. *Frontiers in Nuclear Engineering* 1. doi: 10.3389/fnuen.2022.1080954
- [2] EPRI Project Manager H. Ocken (1999), *Decontamination Handbook*, TR-112352
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- [4] *Decommissioning and Radioactive Waste Processing* : Hitachi-GE Nuclear Energy, Ltd.” Retrieved 5 April 2023. https://www.hitachi-hgne.co.jp/en/activities/waste_treatment/index.html

4.2.5 MEDOC

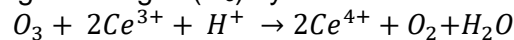
Technology name: Metal Decontamination by Oxidation with Cerium (MEDOC) 

Technology description

MEDOC is a single step regenerative process, which uses the strong oxidation properties of Ce^{4+} . It can be used in either a nitric acid or sulphuric acid medium. 0.4 M of cerium nitrate is used with 2 M nitric acid or 50 mM cerium sulphate can be used with 0.25-1 mM sulphuric acid [1]. Cerium (IV) is added to balance the temperature decrease [2]. This process has no particular affinity to any metals and attacks them equally according to the reaction below. This method is implemented at 40°C and can go up to 80°C. The solution flows through a loop and can be run for several hours up to a couple of days. [1-2]



This leads to attack of the base metal as well, which can lead to higher efficiency of the process. The Ce^{4+} is converted into Ce^{3+} as seen in the reaction, Ce^{3+} is less efficient in attacking the metal as it is a weaker oxidant as compared to Ce^{4+} , and therefore the efficiency of the reaction reduces as more Ce^{3+} is produced. The reduced solution is passed through ion exchange resins which capture the radionuclides along with the dissolved metal ions [2]. The reduced Ce^{3+} can then be regenerated into Ce^{4+} by using Ozone gas (O_3) by the reaction seen below.



This Ce^{4+} can then be reused for further attack on the metal surfaces. The regenerative process can be placed in line with the system loop with the use of a static mixer to mix in the ozone gas. [1]

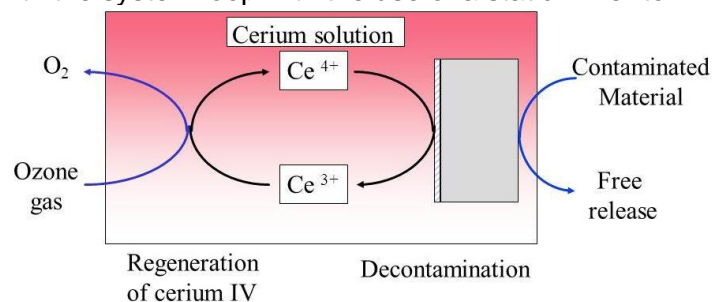
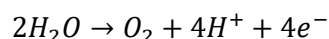
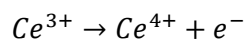
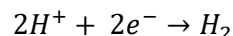


Figure 1: MEDOC treatment process taken from the work done by Ren and Zhang [1]

The contaminated solution would then be considered as a waste when it is saturated in dissolved metals (15 kg/m^3) and it would require to be treated. It can also be treated by electroregeneration such as at the anode:



At the cathode:

**Technical maturity:**

TRL 8 - Undergoing active commissioning

Types of metals treated (including limitations on size and activity)

This technique is suitable for PWR plants containing stainless steel or Ni-alloys. The technique can be used in-situ for maintenance of the reactor core or post-operational clean out and it can be used with all the large components in the system. The technique is not designed for use with systems containing carbon steel as application of this process to carbon steel leads to the production of hydrogen gas.[1]

Product characteristics (including decontamination efficiency)

This method requires the use of either cerium (III) nitrate (solid) and nitric acid (2 M solution) or cerium sulphate (solid) and sulphuric acid (50m M solution), along with an ozone generator and its associated systems. An ozone detector is required as well. The ozone gas is mixed with the liquid solution using a static mixer system, which mixes the two fluids together.

Using such a technique, high decontamination factors of 500-1000 can be achieved [3].

Secondary wastes

Using this technique, the radionuclides are captured in ion exchange resins as well as sludge (60% water content), which are then treated as waste. Indeed, the metals and cerium precipitate as oxides which need to be filtered. The solution itself will also become waste as well as the washing solution, and the water used for the resins. Like CORD, we will also have technological waste and equipment waste such as tools, hoses, valves, etc.

References

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4.2.6 Decontamination gels – Aspigels (CEA)

Technology name: Decontamination gels – CEA 

Technology description

The use of decontamination gels is well established. These gels can, depending on the surface to be treated, be acid or alkaline; oxidising or reducing [1]. Gels are obtained by dispersion of inorganic particles in a solution to form a shear-thinning fluid [2].

These gels are designed to be easily spread using commercial devices, allowing operators to remain at a distance from the contaminated surface. After being sprayed in thin layers (generally 0.5–2 mm thick), gels crack during the drying step in a few hours (8 to 24 hours, depending on the environmental conditions) to form millimetric pieces (Figure 1) containing the contamination and so easily recoverable by brushing or vacuuming (Figure 2). Then a small volume of water or a wipe can be used to eliminate dried gel residues. The optimal gel thickness is 0.8 mm and induces a corrosion of 0.2-0.6 μm of the metallic surface. Around 600-800 g of gel is required to corrode around 0.3-0.4 μm of 1 m^2 of metallic surface. They are used industrially. Indeed, gel technology is mature and products are already commercially available, such as the SPIGEL range from the FEVDI Company [3].



Figure 1: Example of millimetric pieces generated by drying of the gel during decontamination [3]

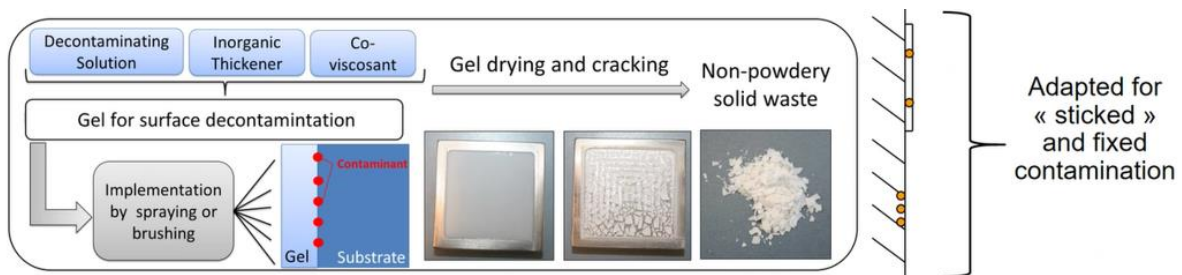


Figure 2: Principles of inorganic gel decontamination technology [2].

Operating principles

The oxidising agent found in this kind of gel is Ce(IV). The redox potential of $\text{Ce}^{4+}/\text{Ce}^{3+}$ for this cation is +1,61 V in nitric acid. Reducing the mineral component leads to a decrease in the amount of solid waste generated by the process [1,2].

A corrosive gel (nitric acid + Ce(IV)) was used to decontaminate 316L stainless steel; this worked well on non-oxidised surfaces but led to inhomogeneous results and residues remaining on the strongly oxidised surfaces (Figure 3). An average corroded thickness of 0.24 μm was achieved following complete drying (which takes a few hours, such that this technique would be practically applicable in real situations), cracks are observed after ~ one hour.



Figure 3: Examples of decontamination gel application and resulting surface appearance on non-oxidised and strongly-oxidised 316L stainless steel (Gossard, CEA) [4].

Use of gel techniques with new decontamination solutions $\text{KMnO}_4 + \text{HNO}_3$ and oxalic acid are now being trialled. Two adapted gel formulations have been realised and are applied successively: one gel containing $\text{KMnO}_4 + \text{HNO}_3$ and one containing oxalic acid. These new formulations are effective on 316L stainless steel, but less than Aspigel 100E. Nevertheless, these new gels may be utilised as an alternative to ASPIGEL 100E, notably in situations where Ce(IV) cannot be used (e.g. not compatible with available secondary waste routes) or if soft decontamination operations are required, i.e. only very slight surface removal required to not deeply corrode the surface.

Table 1: Decontamination efficiency for a range of gel formulations.

Coupon material	Decontamination treatment	Comments	Mass loss	Area treated (cm ²)	Removal (mg/cm ²)
304L	CEA Aspigel		35.1 mg	8	4.39
304L	CEA New gel	2 applications	2.6 mg	8	0.32
316Ti	CEA Aspigel		99.2 mg	4.8	20.67

Technical maturity:

TRL 9 – Proven technology

Types of metals treated (including limitations on size and activity)

An oxidising gel (in presence of an acid or alkali) allows the removal of fixed contamination on metallic stainless steel pieces. However, the oxide layers on stainless steel surfaces such as Inconel or Incolloy in primary circuits can resist the treatment. An alkali reducing gel used alongside an oxidising gel can destabilise well-fixed oxide layers. If the decontamination factor is not optimised, it is possible to alternate oxidising and alkali gels in cycles to eliminate all contamination [1].

The thickness of the deposited layer is an important parameter to consider. If the layer is too thin, the gel will not crack enough (weak internal mechanical tension) and the flakes will remain strongly attached to the surface (no delamination). Moreover, the decontamination depth will be low. If the layer is too thick, the gel may take too long to dry and may begin to flow [3].

While spraying is important to treat large surfaces, it is clearly not an option for smaller objects with complex geometries (spring-like structures, or items with holes or internal surfaces for example) [3].

Different type of metallic waste can be treated using decontamination gels:

- Large and planar surfaces with a gel application by spraying using commercial spraying device. The gel can be applied with a speed of $4 \text{ m}^2 \cdot \text{min}^{-1}$.
- Small and complex geometry items can be coated by immersion of the piece for a few minutes into a bath of gel or by using the new “magnetic” gel formulation remotely spreadable with a magnet.

Types of metals treated (including limitations on size and activity)

Gels can be used to decontaminate steel or steel alloys such as stainless steel (nitric acid and Ce(IV)), carbon steel (phosphoric and citric acid), aluminium alloys (nitric and phosphoric acid) or lead (acetic acid and hydrogen peroxide). However, the oxide layers on stainless steel surfaces such as Inconel or Incolloy in primary circuits can resist the treatment [1].

Product characteristics (including decontamination efficiency)

Use of Aspigel 400 for the decontamination of slave arm in aluminium.



Figure 4: Decontamination of an aluminium slave arm

Degreasing was necessary before decontamination. The gel application is realised with a paintbrush. With one gel application a DF around 10 is obtained and after 2 gel applications, a DF around 30 is obtained.

The surface was corroded only a few microns after decontamination.

Secondary wastes

Secondary waste is the dried gel after decontamination, around 150-200 g per m² for a metallic surface which can be directly conditioned and stored without any further treatment [2]. Other secondary wastes will include wipes, personal protective equipment (PPE) and a few litres max of water containing contaminated solids.

The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment [2].

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- [2] CEA, Le traitement et la décontamination des structures, des sols et des effluents
- [3] A. Gossard, A. Lilin, S. Faure (2022), Gels, coatings and foams for radioactive surface decontamination: State of the art and challenges for the nuclear industry, Progress in Nuclear Energy, Volume 149, 104255
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4.2.7 Decontamination gels – EASD gels

Technology name: Technology name: EASD® Gel – National Nuclear Laboratory (NNL)



Technology description

Electropolishing is a mature metal surface treatment technology that is commonly applied in a range of industrial applications, including in purification, post-weld treatments, and surface cleaning. This process is typically achieved by immersing a metallic item within a bath filled with a specific electrolyte. Electrical connections are then commonly made to a direct current (DC) power supply. The targeted metallic item is connected to the positive electrical terminal (making it the anode) and a counter electrode is also located within the electrolyte, thus creating an electrochemical cell. Application of an electrical current facilitates the controlled dissolution of the anodic metal surface into the electrolyte. When this same process is applied to radioactive metallic waste items, the radioactive isotopes that have been incorporated into the surface material can also be removed, thus enabling waste reclassification and recycle of the bulk metal.

Electrolytically Assisted Surface Decontamination (EASD®) is an enhanced electrochemical method (developed and patented by the National Nuclear Laboratory (NNL) and C-Tech Innovation Ltd, UK) that can be applied to decontaminate metallic surfaces [1][2]. Several devices have been designed that incorporate this EASD® technology and enable the decontamination process to be applied in-situ to a range of metallic, radioactive waste items commonly identified during nuclear decommissioning programmes, e.g., pipework, tanks and walls/floors.

EASD® Gel is one technology variation that utilises a gel-based electrolyte, most suited to scenarios where localised/specific areas of metallic surfaces or contamination 'hot spots' need to be removed but limited effluent routes are available (e.g. a small, contaminated area on the base of a glove box).

Operating principle

The EASD® Gel treatment process utilises an applied alternating electrical current to facilitate the controlled dissolution of a metal surface, and any associated radionuclides, into a gel-based electrolyte, illustrated in Figure 1. The gel was designed to be simplistic in its composition, thus generating a secondary waste compatible with the native reagents commonly used on nuclear sites, i.e., avoiding a limitation associated with chemical decontamination. Most of the development work linked with this technology has been performed in consideration of, and in collaboration with, Sellafield Ltd; a large, complex, UK nuclear site. The predominant chemical reagent used at this site is nitric acid, thus this has formed the basis of the electrolyte-media used in the EASD® Gel process.

The technique has been successfully demonstrated under radioactive laboratory conditions using metallic Low Level Waste (LLW). Surface removal rates of $0.5 - 0.7 \mu\text{m min}^{-1}$ have been achieved for stainless steel. 10-fold greater removal rates have been demonstrated on mild steel. Table 1 details the results from the experimental work conducted under EU-Project PREDIS, work package 4 [3].

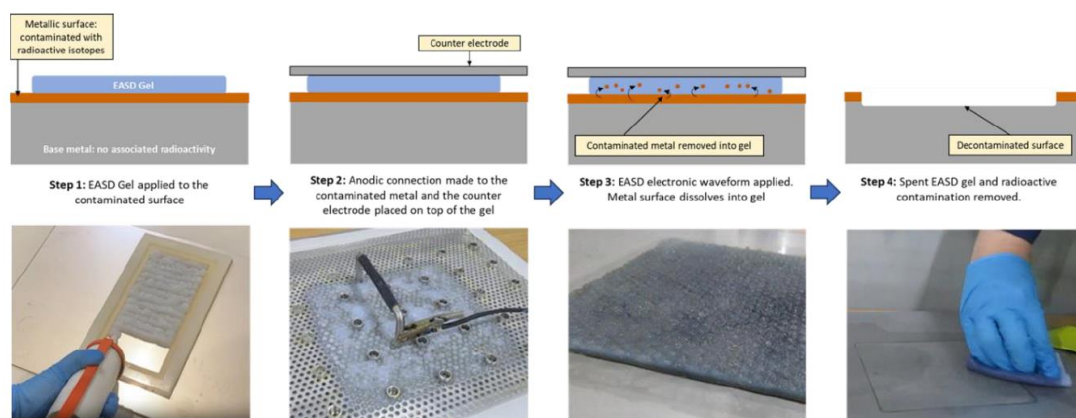


Figure 1: Diagram illustrating the EASD® Gel process

EASD[®] gel has been trialled on 304L and 316Ti steels (Table 1), to test its applicability to a range of potential scenarios. It is most applicable to treatment of localised areas.

Table 1: Decontamination efficiency for the NNL EASD[®] gel formulation on a range of materials.

EU-Project PREDIS coupon	Max. removal rate achieved (µm/min)	Max. removal rate achieved (mg/cm ² /min)
304L-grade coupons corroded and contaminated in a high active liquor simulant	0.14	0.11
316Ti-grade coupons corroded under simulated PWR steam generator conditions	0.83	0.65

Technical maturity:

TRL 6/7 – Technology demonstrated in radioactive laboratory and an engineered prototype made for in-situ testing on a nuclear site.

Types of metals treated (including limitations on size and activity)

EASD[®] gel has been shown to be compatible with a variety of metallic waste (e.g., stainless steels, nickel-alloys, lead etc.)

Product characteristics (including decontamination efficiency)

A range of LLW metallic items have been successfully decontaminated to VLLW / free-release levels in the order of minutes as part of the technology development work (Figure 2). Examples include waste containers used to store and transport radioactive swarf/fuel debris and pipework removed from nuclear facilities. A benchmarking assessment of the EASD[®] Gel technology was also performed against other decontamination technologies currently used at the Sellafield site for hotspot treatment. It was shown to out-perform the other technologies tested when contamination had deeply penetrated into surfaces.

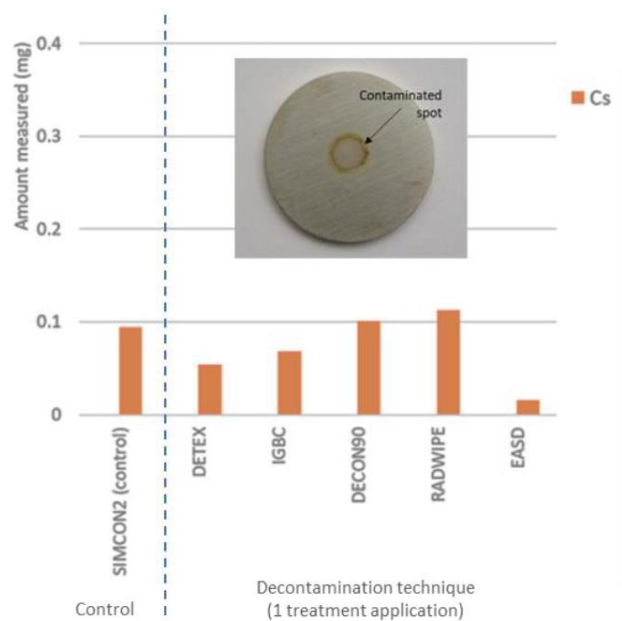
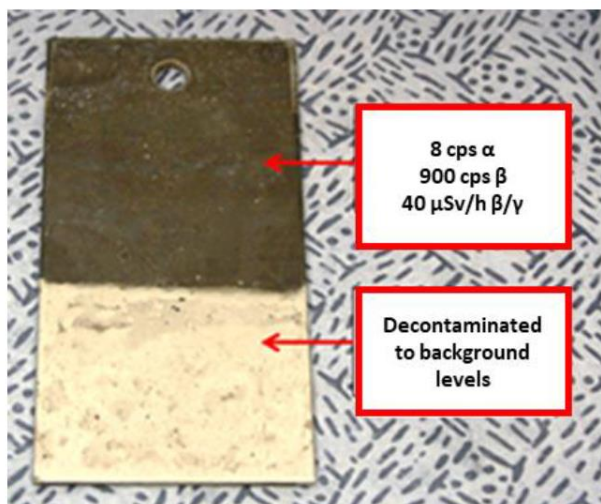


Figure 2: Image (left) of a decontaminated radioactive test coupon and a graph (right) showing the results from a bench-marking assessment which utilised 'SIMCON2-style' artificial test coupons, which replicate fixed contamination [4].

Secondary wastes

The secondary waste is the hardened spent gel after decontamination. Approximately 4 L of gel is required to treat a 1 m² metallic surface. This can be directly conditioned to a solid or liquid waste route or encapsulated. An encapsulation method has been established.

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- [3] PREDIS, Deliverable 4.4, Report on innovative decontamination process
- [4] R. Demmer (1994), Development of Simulated Contaminants (SIMCON) And Miscellaneous Decontamination Scoping Tests, Idaho National Engineering Laboratory

4.2.8 Decontamination foams

Technology name: Decontamination foams 

Technology description

Foams were developed to decrease the amount of liquid effluent after decontamination. They are stable for a few hours and are composed of small amount of foaming surfactant (1 to 3 g/L) and viscosity-enhancing agents (xanthane) [1]. The liquid decontamination foaming solution is usually mixed with 80-90% of gas (air) to generate viscoelastic foams [2].

The foams can be adapted to facilitate spraying (of surfaces), circulation (through pipes) or direct filling (gloves boxes, tanks, reactors, steam generators etc.) [2]

Operating principles

For example, for a steam vapor decontamination, three kinds of foams are applied successively to the metal surface, each with 17% of liquid content [1]:

1. The acidic foam (0.5 M phosphoric acid) allowed the weakening of copper oxide.
2. A second acidic foam (0.4 M oxalic acid) allowed the weakening and the partial dissolution of iron oxide.
3. Last, a combination of 0.08 M oxalic acid and 10 M hydrogen peroxide allowed the treatment of the formed oxalates.

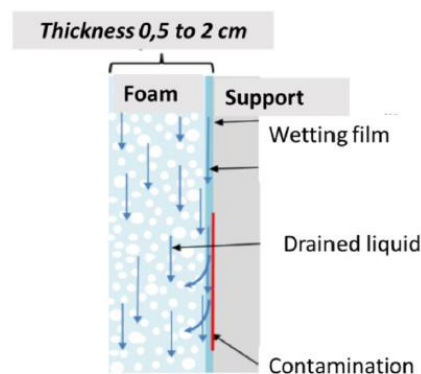


Figure 1: Example of a decontamination with pulverised foam [2]

To increase the viability of the foams and so their efficiency, hydrophile pyrogenic silica nanoparticles (7 nm of diameter) were added instead of xanthane (so the foams remain intact for twice as long) [1].

The use of water with this process is decreased by six to ten times in contrast to chemical washing [1].

Technical maturity:

TRL 9 – Proven technology

Types of metals treated (including limitations on size and activity)

This kind of decontamination foam was used to treat the secondary circuit of a steam generator [1]. It is possible to circulate the foam in a loop and to destroy it using ultrasound before recovering and recycling or to use it in static mode to eliminate an oxide layer [2].

It is challenging to identify the best combination of foaming surfactant and (polymer/particle) additive to adapt the stability (lifetime) of the foam to the expected decontamination time.

Secondary wastes

For the foams, liquid solutions are produced as secondary waste. They could be treated by photocatalysis UV/TiO₂ [1].

The handling of the final liquid secondary waste has also to be carefully evaluated, in term of both liquid recovery after the foam drainage but also post-treatment. After foam degradation, the

residual liquid can be collected. One solution could be the vacuum aspiration of the foam before its complete degradation to avoid these steps, which may be tedious to implement. The post-treatment of the secondary liquid waste can be performed by evaporation to obtain solid and/or sludge to be conditioned. However, the presence of organic compounds can make this operation complicated. Optimisation of the initial foam composition (concentration and nature and the surfactant/thickener) could be a reflection as well as the degradation of the organic compound before evaporation using specific chemicals or photocatalytic processes [2].

The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment.

References

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4.3 Thermal technologies

4.3.1 Nuclear thermal technologies

Melting technologies have been implemented at a wide range of facilities, and are primarily used for treating mixed lower activity wastes. This section contains datasheets for technologies allowing to melt metal.

4.3.1.1 Plasma burning and melting (PACT process)

Technology name: Plasma burning and melting (PACT process)

Technology description:

The PACT (Plasma Arc Centrifugal Treatment) process from RETECH is an air transferred plasma furnace, heating a refractory rotating crucible [1]. The PACT system is based on a design used for metal remelting, but has been adapted to treat lower level mixed radioactive waste, including metals [2, 3]. An 8-foot diameter PACT has operated in Zwiilag (Switzerland) since 2004 (TRL 9) for the treatment of LLW from hospitals and NPPs [4], and a second facility operates (since 2005) in Japan at the Tsugura nuclear power plant [5]. Figure 1 shows an overview of the PACT system showing the main components of the facilities. The system operates in three main stages. Firstly, the drums of radioactive waste are cut up into smaller pieces, which are then (drum and waste) fed into the centrifuge furnace. Here the plasma torch heats the waste to temperatures of up to 20,000°C [4]. This destroys all organic material (removed as off-gas) and melts inorganic components, including metal. If necessary, to enable vitrification of the inorganic component, glass frit is added to the furnace. The centrifugal action of the furnace ensures the molten waste stays in the path of the plasma torch, and is evenly melted. The centrifuge also removes the need to tilt the furnace to drain out the slag after melting. Instead, to drain the furnace, the centrifuge is slowed and the melted waste is allowed to fall through a central drainage hole into the storage/disposal canister [7]. Any off-gases created are separated and treated with an off-gas treatment system (filters and after-burner) before release.

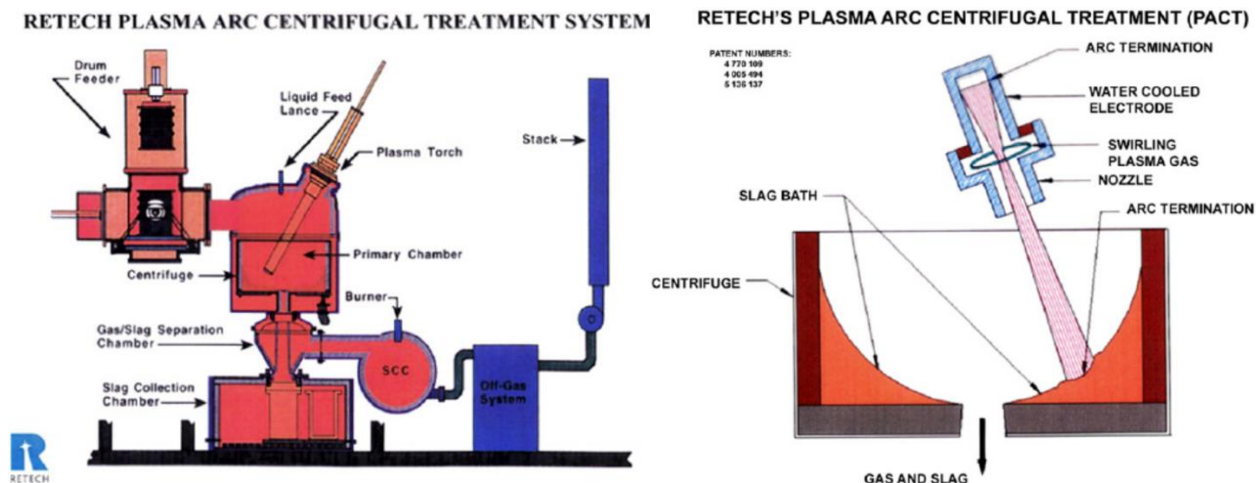


Figure 1: Schematic of the PACT system, from [6]

Technical maturity:

TRL 9 – Proven technology

Types of metals treated (including limitations on size and activity):

Plasma melters generally treat mixed waste feeds, with metal only forming a minor component of the waste. The Zwiilag facility routinely treats wastes held in steel drums. The drums are fed unopened into the furnace and the metal is melted along with the mixed non-metallic waste. The drums themselves can also contain metallic waste items.

Product characteristics (including decontamination efficiency):

The primary product from plasma melting is a homogenous monolithic glass, that contains the inorganic constituents of the waste, including non-volatile radionuclides [7]. The metallic

components can be oxidised and incorporated into the glass, although a metallic phase may remain.

Secondary wastes:

The main secondary wastes generated by plasma melting are the off-gases and associated off-gas scrubbing wastes (wet and dry filters) [7]. The process typically creates around 2% secondary waste by mass [8].

The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment. A large amount of refractory wastes will be also produced [9].

References

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- [9] Orano, Plan national de gestion des matières et déchets radioactifs 2016-2018, Article 49 de l'arrêté PNGMDR du 23 février 2017 Rapport d'étape présentant l'état d'avancement à fin 2018 des travaux de développement du procédé d'incinération / vitrification (PIVIC) visant à conditionner les déchets MA-VL organiques riches en émetteurs alpha, Note technique référence DM2D NT 2018-077

4.3.1.2 PIVIC

Technology name: PIVIC**Technology description:**

The PIVIC process works by combining a plasma torch with cold-crucible induction melting. It is a reactor with two parts: a lower part constitutes by a jacketed metal can which is inserted in a sectorised cooling envelope; itself surrounded by a low-frequency cylindrical inductor whose function is to heat the metal phase introduced into the can. The glass is then heated by the metallic phase thanks to the high level of heat transfer at the metal/glass interface. A ceramic coating on the inside of the can provides thermal and chemical protection. A superior part where the introduction chamber is localised as well as at least one plasma torch above the melting-vitrification oven to realise the combustion of the organic fraction under oxygen (combustion chamber). The combustion of the waste is not done directly under the flames but about them, in an appropriate thermic environment. PIVIC is completed by a gas treatment apparatus with an air dilution to lower the gas temperature, a pre-filtration using an electro-filter, a series of HEPA filters and a washing column [1]. Figure 1 shows a schematic of the PIVIC process, highlighting the main stages in the process. At stage 1, the waste is lowered in a metal basket from the top of the plant where a plasma torch (marked 2) combusts organics and other volatiles, which are removed in the off-gas (marked 3). Following a period of combustion, the remaining non-combustible material (including metal) is then lowered into the disposal cannister (marked 4) where it is heated via cold crucible direct induction melting (CCIM) (marked 5) to produce a melt. A current is induced in the metal, and this in turn melts the metal and glass frit [2]. The direct melting of the waste within the final disposal can removes the need to discharge the glass after pouring. This removes the viscosity limitations present in conventional CCIM systems and greatly increases the range of wastes accepted by PIVIC.

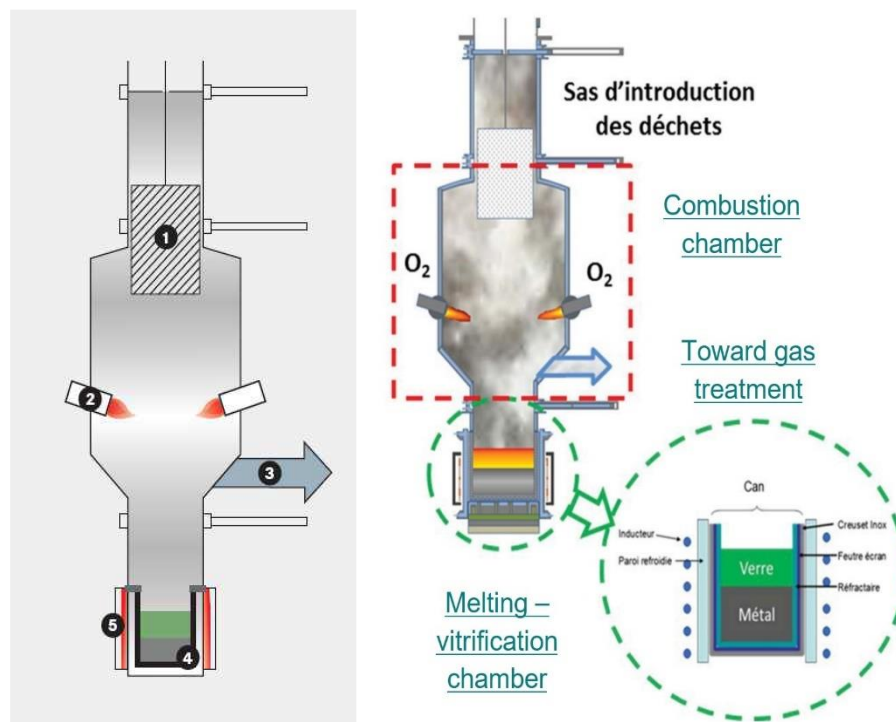


Figure 1: Overview of the PIVIC process, from [1-2]

Technical maturity:

TRL 5 - Pilot Scale

Types of waste treated (including limitations on size and activity)

The PIVIC process has been designed to treat a wide range of wastes: mixed organics and metal, inorganics, PCM, highly chlorinated waste (PVC), and mixed liquids (oils, sludges, etc.). The facility can accept metallic cannisters of mixed waste (including PCM).

The presence of metals and chlorine in significant quantities in certain organic waste materials can lead to the formation of metal chlorides, a highly corrosive product that condenses on the cold walls of gas treatment units [1].

Product characteristics (including decontamination efficiency)

Once melted the metallic and glassy components separate to produce a bi-phasic can (shown in Figure 2), with the metal ingot at the bottom and the glass layer on top, which contains the non-metallic inorganic constituents [2, 3]. The actinides partition into the glass, separating them from the metal and reducing the criticality risk. The fission products remain in both the glass and the metal phases. As the vitrification step is reliant on induction of a current within the waste, it is essential that the waste materials contain some metallic components.

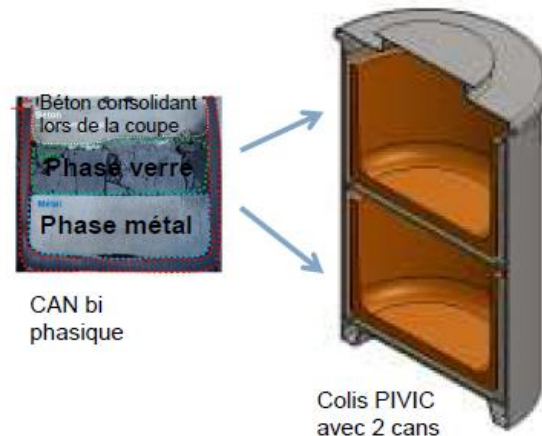


Figure 2. The bi-phasic PIVIC can, showing the metal and glass components, from [2]

Secondary wastes

The main secondary wastes from the PIVIC process are associated with the off-gas filtration system and include liqueurs from the wet scrubbers, and solid filters (metal and HEPA) [2]. It is possible that much of the secondary waste could be treated directly by the PIVIC process, removing the need for any additional facilities, and increasing the efficiency of the process. The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment.

References

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4.3.1.3 Induction metal melting

Technology name: Induction metal melting**Technology description**

Induction melting involves inducing electric currents in a material, leading to resistive heating. The heating can either be indirect or direct [1,2]. Indirect induction melters operate by heating the crucible into which the waste is then placed (and melted indirectly by the heat of the crucible). A few facilities use this technology: Cyclife Sweden, Cyclife France, CARLA (Germany), GERTA (Germany), and EnergySolutions Bear Creek Facility [3-8]. Indirect induction melters operate by heating the crucible into which the waste is then placed (and melted indirectly by the heat of the crucible). Direct induction melters (or cold crucible induction melters) use an unheated crucible and directly induce currents in the waste, to induce heating and melting, shown schematically in Figure 1 [9].

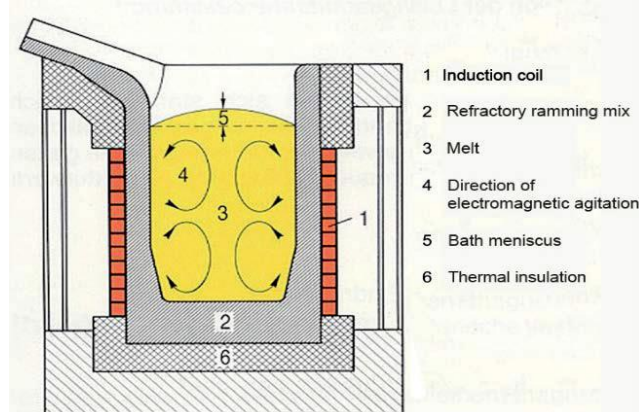


Figure 1. Direct induction melting [9]

The process provides effective decontamination, as many contaminants move to the dust or to the off-gas (e.g., volatile isotopes of H, C, Sr, Cs, etc.) or to the slag (isotopes of U, Th, Pu, Cm etc.). Metallic elements, such as Fe, Ni and Co, including their radioactive isotopes, partition into the metal melt and are homogenised, where surface contamination is transformed into volume contamination.

The volume reduction corresponds to a factor from 6 to 10 [10]. At CENTRACO (France), around 600 tonnes of waste are treated each year, while 4500 tonnes of waste each year are treated by Cyclife Sweden [11].

Technical maturity:

TRL 9 – Proven technology

Types of metals treated (including limitations on size and activity)

Induction metal melters can treat a wide range of ferrous and non-ferrous metals containing both surface and bulk contamination and/or activation [9]. Most metal melting facilities are limited to treating lower activity wastes and there are often restrictions on the presence of certain elemental impurities (e.g. no mercury).

Capability to operate under inert atmosphere

Vacuum induction melting furnaces are widely used to produce high purity alloys, as this allows for the removal gaseous impurities.

Operation under an inert atmosphere is also possible. However, oxidation of impurities by atmospheric oxygen, allowing them to form a slag, is an important process in induction melting that would not occur under an inert atmosphere. Therefore, operation under a vacuum or inert atmosphere is only favourable if the removal of non-gaseous impurities is not desired.

Product characteristics (including decontamination efficiency)

For lower activity metallic waste, the treated metal may be released to the open market as scrap metal ingots. Alternatively, metal that cannot be sufficiently decontaminated can be used to make

metallic items for re-use in the nuclear industry (e.g. waste drums) [9]. The technique can also be used for to reduce the volume and improve the morphology of the metal (removing voids) prior to disposal.

Some facilities (e.g. GERTA) can also treat metals that are chemically contaminated (e.g. asbestos, PCB, mercury [7]).

Secondary wastes

The main secondary wastes produced from metal melting are ingots. Other wastes include slag, which may contain many of the non-volatile radionuclides, as well as refractory material (from the oven and from the ladle). Additionally, the off-gas treatment system will produce secondary waste (ashes, filters, and liquid scrubbers) containing reactive radionuclides that were volatilised during the melting process (such as Cs-137 and C-14) [9]. The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment. If a cutting step is mandatory prior treatment, additional waste will result from pre-treatment including equipment, other waste arising from the sorting process.

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- [9] Areva, CEA and GSL (2018), Current Status of Thermal Treatment of Radioactive Waste Streams in the European Union, Theramin Deliverable D2.3
- [10] <https://www.cyclife-edf.com/cyclife/organisation/cyclife-france/nos-solutions/fusion>
- [11] Hong, S.-H., Hwang, S., Kim, C.-W. (2017), Study on Induction Melter Technology to Treat Decommissioning Metallic Radwaste Generated From Kori Unit 1, Proceedings of the Korean Radioactive Waste Society Conference, 273-274

4.3.2 Non-nuclear melting technologies

Different metal melting technology owners were contacted to establish whether the technologies had been used previously within the nuclear industry and, if not, how applicable these technologies may be for decommissioning waste from nuclear reactors. Information provided is presented below within technology datasheets for Electric Arc Furnace Melting, Rotary furnace melting, immersion melting and Plasma Arc Melting.

4.3.2.1 Electric Arc furnace melting

Technology name: Electric Arc Furnace Melting

Technology description

Electric arc furnaces (EAFs) are commonly used outside the nuclear industry for recycling of steel and iron and are suitable for scrap with high concentrations of residual elements. [1]

EAFs use electrodes that are lowered to strike an arc on the cold scrap; the electrical system automatically controls the level of the electrode, lifting and lowering each individual electrode according to the electrical settings. The arc provides heat by radiation and current resistance (through the metal) to melt the scrap.

EAFs can be divided into direct, indirect and submerged categories. In indirect furnaces, the arc jumps directly between the electrodes, whereas in direct and submerged furnaces, the arc jumps to the charge. In submerged furnaces, the electrodes are submerged in the charge. The temperature in indirect furnaces is lower than direct furnaces so indirect furnaces are most suitable for lower melting point metals.

EAFs can also use AC or DC. AC voltage crosses zero twice in each cycle, resulting in the arc starting and extinguishing process twice a cycle. This results in an unstable arc. In DC, there is no arc extinction and the arc light is very stable. For direct AC furnaces, a three-phase power supply is used and so three graphite electrodes are required. Only two are needed for DC furnaces. [2]

Energy losses can be high due to the large surface area to volume ratio of the furnace. However, some designs (those with submerged electrodes) can operate continuously which improves energy efficiency.

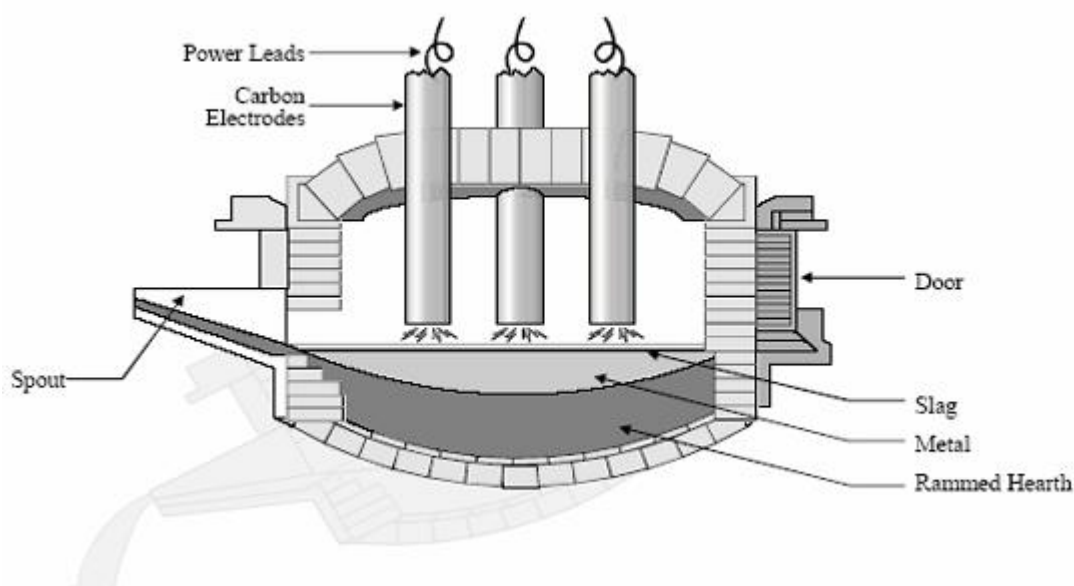


Figure 1: Electric arc furnace [1]

Waste loading process	
The waste loading process can be manual or remote depending on the design of the furnace.	
Types of metals treated (including limitations on size and activity)	
EAFs are able to treat a wide range of ferrous and non-ferrous metals and are generally more tolerant of impurities than induction furnaces.	
Capability to operate under inert atmosphere	
Oxidation of impurities by atmospheric oxygen, allowing them to form a slag, is an important process in electric arc melting that would not occur under an inert atmosphere. Vacuum EAFs are known but these are only used to produce materials with higher chemical and mechanical homogeneity, through the removal of gaseous impurities, from metal ingots that have already been produced. Operation under a vacuum or inert atmosphere is possible but is only favourable if the removal of non-gaseous impurities is not desired.	
Consumable Materials required	
Electrodes and refractor materials.	
Secondary wastes	
The main secondary wastes produced from metal melting are ingots. Other wastes include slag, which may contain many of the non-volatile radionuclides, as well as refractory (from the oven and from the ladle). Additionally, the off-gas treatment system will produce secondary waste (ashes, filters and liquid scrubbers). The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment. If a cutting step is mandatory prior treatment, additional waste will result from pre-treatment including equipment, other waste arising from the sorting process.	
TRL	9, but only deployed outside of nuclear industry
References	
[1] BCS (2005), Incorporated: <i>Advanced Melting Technologies: Energy Saving Concepts and Opportunities for the Metal Casting Industry</i>	
[2] K. Zhang (2021), <i>Electric Arc Furnace VS Submerged Arc Furnace</i>	

4.3.2.2 Rotary furnace

Technology name: Rotary Furnace Melting

Technology description

Rotary furnaces are batch furnaces that generally utilize oxy-fuel burners and limit the volume of off-gases. The rotary furnace design gives high utilization of the input energy compared with the stationary furnace: transferring heat via both radiation and conduction [1].

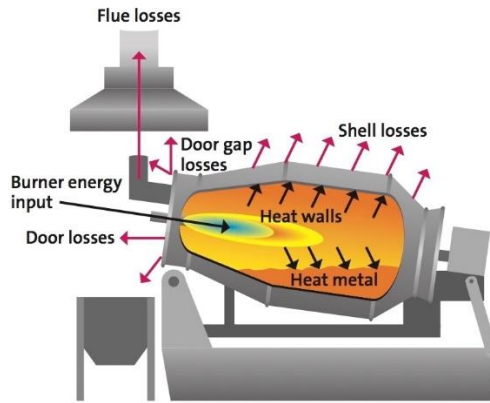


Figure 1: Rotary Tilt Furnace [2]

Types of metals treated (including limitations on size and activity)

Rotary furnaces can treat a wide range of ferrous and non-ferrous metals. Rotary furnaces are not currently used in the nuclear industry: consequently, there are no defined limits on activity

Capability to operate under inert atmosphere

Technology cannot operate under an inert atmosphere as oxygen is required for combustion for fuel, although this is provided by the burner.

Consumable Materials required

Refractory materials

Secondary wastes

The main secondary wastes produced from metal melting are ingots. Other wastes include slag, which may contain many of the non-volatile radionuclides, as well as refractory (from the oven and from the ladle). Additionally, the off-gas treatment system will produce secondary waste (ashes, filters and liquid scrubbers). The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment. If a cutting step is mandatory prior treatment, additional waste will result from pre-treatment including equipment, other waste arising from the sorting process.

TRL

9, but only deployed outside of nuclear industry

References

- [1] BCS (2005), Incorporated: *Advanced Melting Technologies: Energy Saving Concepts and Opportunities for the Metal Casting Industry*
- [2] M. Lawrence, R. Hendershot, A. Guha, M. Dines (2020), *Digital Twin Methodology Improves Performance and Yield in an Aluminium Tilt Rotary Furnace*, lightmetalage.com

4.3.2.3 Immersion melting

Technology name: Immersion Melting**Technology description**

The heat is generated by combustion or electrical resistance inside a tube submerged in molten material. The heat is transmitted to the charge through the wall of the tube by conduction. Heat losses are minimised as the heating element is entirely surrounded by the charge.

Immersion heat tubes are typically made of metallic materials that have high thermal conductivity and are coated with ceramic or cement materials to resist corrosive attack by the molten metal. When melting aluminium or other higher temperature melting materials, heavier ceramic coatings are applied because these molten materials act more aggressively on the tubes. The ceramic coatings, however, act as a thermal barrier and lower the efficiency of the immersion heater. The maximum temperature achievable is thus limited by the materials used and so immersion heating is typically only used for low melting point metals [1].

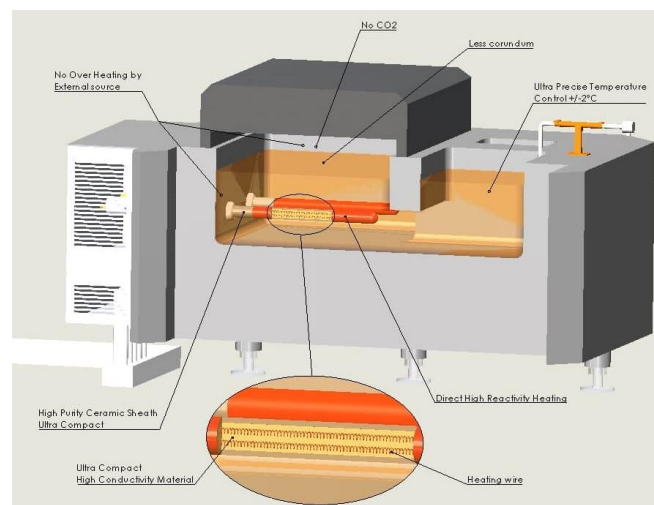


Figure 1: ATHERM immersion heater [2]

Types of metals treated (including limitations on size and activity)

Low melting point metals (i.e., aluminium and zinc)

Capability to operate under inert atmosphere

Technology can operate under an inert atmosphere but doing so would minimise dross formation, meaning impurities, including radionuclides, are more likely to remain within the metal. This may or may not be favourable depending on the waste stream.

Consumable Materials required

Immersion elements require replacing every one-two years. [2]

Secondary wastes (solids)

Direct heating minimises metal losses to oxides, corundum and drosses meaning less secondary waste is produced than other melting technologies. [2] However, lower dross production is likely to result in a higher activity main product.

Gaseous & Liquids Effluent

The off-gas treatment system will produce secondary waste (ashes, filters and liquid scrubbers).

TRL

9, but only deployed outside of nuclear industry

References

[1] BCS (2005), Incorporated: *Advanced Melting Technologies: Energy Saving Concepts and Opportunities for the Metal Casting Industry*[2] Atherm, Immersion Heaters for Light Metals, <https://www.atherm.com/aluminium-immersion-heating/>

4.3.2.4 Plasma Arc Melting

Technology name: Plasma Arc Melting (PAM)**Technology description**

The plasma arc melter is a device to melt a substance by low-temperature plasma flow, typically created by an electric arc heater (plasmatron). Various direct current (DC) and alternating current (AC) plasmatrons are used in plasma furnaces. In large-scale plasma furnaces, several plasmatrons are used to provide more homogeneous heating [1].

Arc plasma is a temporary state of a gas. The gas gets ionized by electric current passing through it and it becomes a conductor of electricity. In ionized state, atoms are broken into electrons and cations and the system contains a mixture of ions, electrons and highly excited atoms [2].

There are three types of the plasma furnaces: plasma furnaces for melting in a ceramic crucible; plasma furnaces for melting in a crystalliser; plasma furnaces for melting in a scull. Melting in a crystalliser is primarily used for metal refining and melting in a scull for casting. Ceramic crucible furnaces are thus most suited for use in the nuclear industry as they are used mainly for melting steel, nickel-based alloys and waste metals with alloying additions as well as for grey cast iron smelting. Argon is usually used as the plasma forming gas.

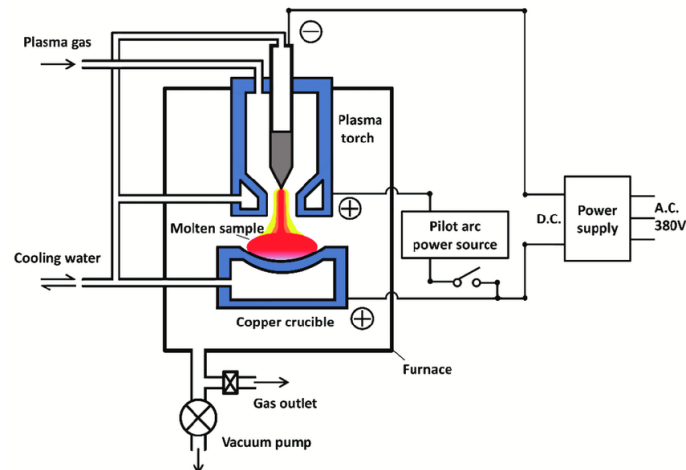


Figure 1: Schematic of Plasma Arc Melter [3]

Types of metals treated (including limitations on size and activity)

PAMs are able to treat a wide range of ferrous and non-ferrous metals and are generally more tolerant of impurities than induction furnaces. PAMs are not currently used in the nuclear industry: consequently, there are no defined limits on activity.

Consumable Materials required

e.g. refractory materials or electrodes

Secondary wastes

The main secondary wastes produced from metal melting are ingots. Other wastes include slag, which may contain many of the non-volatile radionuclides, as well as refractory (from the oven and from the ladle). Additionally, the off-gas treatment system will produce secondary waste (ashes, filters and liquid scrubbers).

The technique will also produce a quantity of general consumable soft waste, such as cleaning equipment and personal protective equipment. If a cutting step is mandatory prior treatment, additional waste will result from pre-treatment including equipment, other waste arising from the sorting process.

References

- [1] Y.S. Svirchuk, Plasma Arc Furnace, Thermopedia
 [2] M.J. Gallagher, A. Fridman (2011), *Fuel Cells: Technologies for Fuel Processing*, Chapter 8 - Plasma Reforming for H₂-Rich Synthesis Gas, Pages 223-259

[3] X.L., Guo & Yu, Jianbo & Hou, Yuan & Zhang, Yujia & Wang, Jiang & Li, Xia & Liao, Hanlin & Ren, Zhongming. (2018). *Manganese Removal from Liquid Nickel by Hydrogen Plasma Arc Melting*. *Materials*. 12. 33. 10.3390/ma12010033.

4.4 Conclusion

Different techniques were developed over the years to decontaminate metallic waste. The main categories are mechanical decontamination, chemical decontamination, and thermal treatment. Technologies can also be used in combination to achieve more effective decontamination: for example, mechanical decontamination before chemical decontamination. Some technologies are already used in the nuclear field such as jet washing, sand blasting, laser decontamination, chemical baths and CORD, while others are still in development such as PIVIC, COREMIX and EASD® gels.

Within PREDIS WP4, development activities focused on chemical decontamination with the use of COREMIX-HP and gel decontamination (Aspigel and EASD® gels). While COREMIX-HP is still at laboratory scale (TRL 2-3), it is derived from CORD which is at TRL 9. Aspigel is already commercialised and EASD gels are at TRL 7. Further development and demonstration of these technologies is therefore needed for them to be used industrially by End Users; the analogous experience reported here suggests that this should be feasible.

The following non-nuclear melting technologies are also presented within this report following engagement with technology providers: Plasma Arc Melting, rotary furnace, immersion melting, Electric Arc Furnace Melting. These technologies could be of interest, but require further evaluation for nuclear use.

5 Economic and Environmental Impacts of Metal Decontamination

Information compiled through other tasks within PREDIS WP2 and WP4 has been used to evaluate the potential impact of using the metal treatment technologies studied in PREDIS to manage the inventory reported in Section 2 [10]. This section presents the approach to, and the results of, this economic and environmental analysis of metal decontamination techniques. This analysis, also termed value assessment, brings together research relating to decontamination efficiency, volume of secondary waste, throughput, waste loading, cost and other relevant process and waste product characteristics to form a picture of the overall performance of the metal decontamination technologies subjected to this exercise. Meaning is given to these results by comparing them with current waste management practices to provide conclusions that are relevant to, and easily understood by end-users and decision-makers.

This section supersedes Milestone MS25 [11] and is structured as follows:

- A summary of the value assessment principles and methodology is provided in Section 5.1.
- The scope of value assessment activities is defined in Section 5.2.
- The value assessment results are summarised in Sections 5.3 and 5.4, for COREMIX-HP and the two decontamination gels studied in PREDIS (Aspigels and Electrolytically Assisted Surface Decontamination (EASD) gels), respectively.
- Detailed results from the value assessment workshops reported under MS25 [11] can be found in the tables in Appendix 2.

5.1 Value Assessment Principles and Methodology

Value assessment is a form of multi-criteria cost benefit analysis that provides a methodology for assessing and comparing the technical, economic, and environmental performance of alternative waste management options. Value assessment was used to perform a strategic analysis of the performance of alternative waste management options studied under WP4. The full methodology is presented in references [12] and [13].

The value assessment process is outlined in Figure 6. For WP4, the process started with the identification of treatment and conditioning technologies of metallic radioactive wastes (called variant scenarios) for comparison with the typical current waste management approach used for these wastes, called the baseline scenario. These scenarios and the rationale behind their selection are presented in Section 5.2.1. This selection of waste type/technology combinations encompasses the first two steps in the process outlined in Figure 6.

Having identified representative scenarios, it was necessary to develop a list of attributes, or criteria, covering potential areas that may differentiate technologies from the current waste management approach based on cementation. To make the analysis more targeted and systematic, it was also necessary to identify the relevant stages in the waste management lifecycle. These are discussed and summarised in Section 5.2.2. A list of technology attributes considered for this exercise and justification for significant exclusions are presented in Appendix 1.

The assessment was done on a comparative basis to allow comparison of each technology against its respective baseline, rather than being compared against each other.

A gap analysis of information available for each scenario was carried out and additional data was requested from project partners when needed. This fed into an internal value assessment, which was presented and finalised during a dedicated value assessment workshop held in February 2024 and attended by the following PREDIS WP4 Partners:

- CEA
- GSL (Organiser)
- IMT Atlantique

- NNL
- University of Manchester

During the workshop, tables were produced to capture discussions and these are presented in Appendix 2 as the detailed outcome of this exercise.

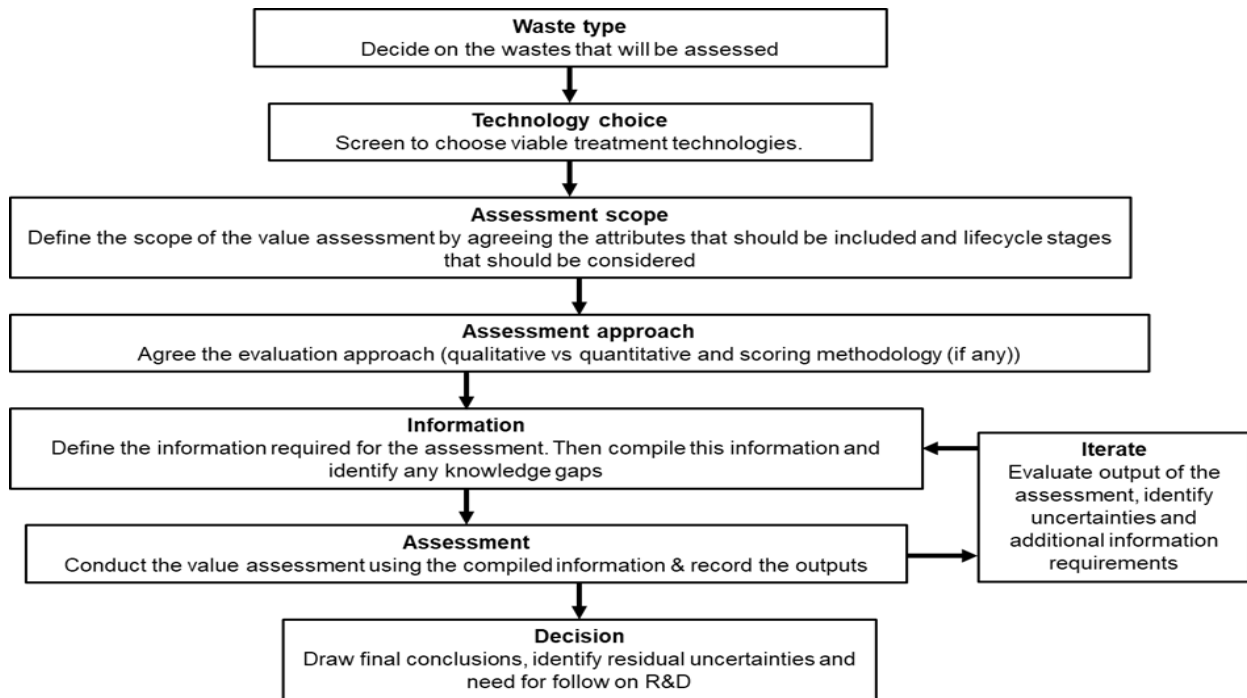


Figure 6: Flow Chart Summary of the Value Assessment Process

5.2 Value Assessment Scope: Scenarios, Attributes and Lifecycle Stages Selection

5.2.1 Scenario Identification and Selection

Scenario identification was based on a review of previous project outcomes, namely:

- Inventory data from Milestone 22 produced under Task 4.3.1 [14].
- Secondary waste information from Milestone 24 [5].
- Technology information from the datasheets produced under Milestone 23 [7] and updated in Section 4.
- Life Cycle Analysis (LCA) / Life Cycle Costing (LCC) scenarios discussed with the University of Manchester (UoM) during a workshop held on 27/09/2023 [15].

Technology combinations that have been modelled as part of the PREDIS LCA/LCC work were previously developed in consultation with individual WP Partners and have been included in the value assessment. The resulting scenarios are aligned with those studied by the WP4 PREDIS research partners, and cover three of the decontamination technologies studied, namely:

- COREMIX-HP (Section 4.2.4).
- Inorganic decontamination gels, Aspigels (Section 4.2.6) developed by the CEA.
- EASD gels (Section 4.2.7), developed by NNL.

It is assumed that:

- For COREMIX-HP the final waste product can be recycled (i.e. released from nuclear controls) or disposed of in a near-surface disposal facility as VLLW.

- For Aspigels, the final product can be disposed of in a near-surface disposal facility and the gel byproducts can be placed in a small container in a canister with other solid wastes.
- For EASD gels, the final product can be disposed of in a near-surface disposal facility and the gel byproducts can be grouted.

Secondary waste generation (e.g. filters, precipitated solids) are included in the scope of value assessment. However, they are generally managed via well-established routes.

Table 1 presents the scenarios analysed in this economic and environmental assessment. Each scenario was allocated a number, based on the following convention:

- The first number refers to the Work Package (WP4).
- The second number refers to the technology type.
- The third number refers to the treatment output.
- Scenarios with the label “B” represent the baseline for waste type “x”. For example, scenario 4.1.1.B is the baseline scenario for the size reduction, packaging and cementation of a steam generator.

Baseline scenarios were selected for each technology, thus enabling comparison of the new treatment and conditioning technologies studied against a consistent baseline. The main factors used in determining the baselines were:

- Realism: the baseline needs to reflect current waste management practices.
- Data availability: sufficient data needs to be available to establish a baseline against which other scenarios can be compared.
- LCA/LCC modelling: the baseline needs to align, as far as possible, with that modelled in the LCA/LCC.

The same baseline was chosen for all the technologies studied: size reduction, packaging, and cementation (potential for use of mobile cement encapsulation plant) resulting in ILW packages. The resulting waste is cemented in 500 L drums and then disposed of in a geological disposal facility (GDF). The baseline is presented in Table 1 below.

Table 1: Work Package 4 Value Assessment Scenarios

Waste type / example	Scenario ID	Treatment technology	Scenario origin and research organisation	Treatment output
Bulk, complex geometries, e.g. steam generator	4.1.1	COREMIX-HP	LCA/LCC, D4.1 IMT Atlantique	Full decontamination – cleared for recycling.
	4.1.2	COREMIX-HP	LCA/LCC, D4.1 IMT Atlantique	VLLW metal Packaging in ISO containers for disposal at a near-surface facility (not cemented).
	4.1.B	Size reduction, packaging and cementation.	LCA/LCC	500L cemented drums Disposal at a GDF
Planar metals, e.g. hot cell walls	4.2.1	Decontamination gels (CEA)	LCA/LCC CEA	VLLW metal Packaging in ISO containers for disposal at a near-surface facility (not cemented). CEA byproduct is ILW/LLW – placed in small container in canister with other solid wastes.

Waste type / example	Scenario ID	Treatment technology	Scenario origin and research organisation	Treatment output
	4.2.2	Electrolytically Assisted Surface Decontamination (EASD) gels (NNL).	LCA/LCC NNL	VLLW metal Packaging in ISO containers for disposal at a near-surface facility (not cemented) NNL gel byproduct is ILW/LLW – grouted product.
	4.2.B	Size reduction, packaging and cementation	LCA/LCC	500L cemented drums Disposal at a GDF

5.2.2 Attributes and Lifecycle Stage Selection

Definition of assessment criteria is based upon the selection of a number of attributes of the waste management and disposal lifecycle that are common to each scenario but also differentiate between the performance of the novel and baseline technologies. An important aspect of this exercise was to prevent “double counting” of weaknesses or benefits. For example, higher waste loadings may reduce the quantity of waste transported, stored, and disposed of, thus impacting operational and transport safety as well as storage and disposal costs. The increased waste loading may therefore result in benefits against several attributes across the waste lifecycle.

The attributes presented in Appendix 3 of [10] were used as the starting point of this exercise. Discussions with the University of Manchester [15] led to the identification of non-differentiating attributes, and therefore to their exclusion from the evaluation.

The LCA and LCC analyses have focused on attributes for which benchmarked data against carbon footprint were available. However, value assessment can consider a wider set of attributes because it can take account of qualitative as well as quantitative evaluations and is based on a relative assessment against the baseline scenario. Therefore, the outputs of value assessment only need to determine if the technologies have benefits in comparison with the baseline, which represents conventional practice. A full table of attributes is presented in Appendix 1, which includes a justification for the exclusion or inclusion of each attribute.

For each attribute, a number of quantitative or qualitative metrics were identified (Appendix 1). This ensured that the assessment was proportionate and targeted, and that attributes were clearly defined. Clear definition of attributes, including assumptions and exclusions, contributes to achieving a rigorous and systematic evaluation, whilst also helping to prevent double counting.

The following sections present the conclusions that can be drawn from the value assessment, highlighting differences between each sub-scenario (4.1.1 and 4.1.2, and 4.2.1 and 4.2.2) where relevant. Conclusions agreed at the workshop and those drawn following subsequent review are differentiated.

The initial assessment carried out prior to the workshop did not include weighting of criteria. Such weighing depends on the priorities of each individual Waste Management Organisation (WMO). Therefore, the conclusions drawn below are “weighting neutral”. An example of weighted results is provided for illustration purposes in Section 5.5.

5.3 Discussion of the Economic and Environmental Impacts of COREMIX-HP

The following set of assumptions was agreed during discussions of the crosscutting criterion:

- Three decontamination cycles would be necessary to allow reclassification as VLLW.
- Six to seven decontamination cycles would be necessary to allow free release of materials.
- Decontamination is conducted *in situ* and size reduction occurs after decontamination.
- A typical steam generator weighs around 300 tonnes and is made of Inconel 600 or 690. The surface area for decontamination is assumed to be 4700 m².

- The market price of Inconel 600 or 690 is assumed to be around 20£/kg [16].
- For the purpose of value assessment, costs expressed in Euros are considered to be broadly similar to those expressed in Great British Pound (GBP).
- Downgrading the disposal requirements and the waste category results in a decimal reduction in disposal price. For instance, near-surface disposal of borderline ILW/LLW would cost ten times less than deep geological disposal of the same waste. Conversely, disposing of the same waste as VLLW to a surface facility would cost ten times less than near-surface disposal (and hence cost one hundred times less than disposal to a GDF).

Steam generators (selected as representative waste for the assessment of the COREMIX(-HP) decontamination process) with a history of tube failure and subsequent blockage¹ are unlikely to achieve full decontamination since the decontaminant cannot reach the condemned area. In such an instance, obstructed tubes have been decontaminated individually, without detriment to the overall decontamination of the steam generator, resulting in re-classification to VLLW [17]. Decontamination levels achieved in instances where significant radionuclide diffusion (e.g. Co-60 or tritium diffusion) is present may not be as high as in other instances, as demonstrated by preliminary results obtained by IMT Atlantique. Dissolution of the base metal would partially remove such contamination but would come at the detriment of secondary waste generation; material recycling within the nuclear industry (leading to slightly less stringent release thresholds compared to free release) was mentioned as a possible route to recycling in such instances.

5.3.1 Operational Safety

Operational safety considerations span treatment and conditioning stages in their entirety.

Treatment, under baseline assumptions, comprises size reduction activities necessary to render waste suitable for conditioning. Such activities, in the instance of a steam generator, would usually be undertaken in an active environment, with the controls and restrictions associated with radiologically controlled areas (such as controlled or supervised areas, as defined in the Basic Safety Standards Directive [18]). Metal cutting activities undertaken on metal with intermediate levels of radioactivity and complex geometries incur significant radiological and conventional risks to the workforce.

Characterisation is an essential step in both the variant and baseline scenarios; to demonstrate compliance with waste package specifications for the latter, and to demonstrate compliance with VLLW or free release levels for the former.

Decontamination using the COREMIX process removes the need for metal cutting activities in an active environment since size reduction can be undertaken following decontamination. The need for size reduction may even be totally removed if bulk recycling is available.

However, using the COREMIX process requires dosing of acid solutions and purity control activities during the decontamination process (each cycle takes approximately 24 hours, with a further 24 to 36 hours required for acid destruction and metal ions precipitation [19]), introducing a chemical hazard that is not present under baseline assumptions. Decontamination loop assembly may also be required, depending on the extent to which plant systems, structures and components are re-used. This introduces some conventional risks, albeit well-known and well-controlled, since pipe and pump assembly are very common across a range of industries.

¹ During plant operations, repairs can be attempted on steam generator tubes that leak due to corrosion and other stress factors. However, this is not always successful or achievable; in this instance, the tube is corked, or plugged, to prevent further leakage from the primary to the secondary circuit.

*Overall, the assessment panel concluded that, based on the evidence assembled, operational safety was **better** when using the COREMIX process than under baseline assumptions. The reduction in radiological risk that results from undertaking size reduction after decontamination outweighs the introduction of well-known and well-managed chemical and conventional hazards by the COREMIX process. This conclusion was further substantiated when assuming full clearance, since alloy production from recycled metals is likely to result in lower risk levels compared to smelting from raw ores.*

5.3.2 Environmental Impact

Discussions around the environmental impact of the COREMIX process focused on the relatively significant amounts of chemicals used for decontamination, whilst acknowledging that metal recycling would lead to important energy savings by avoiding smelting from raw ore, which is an energy intensive process. In addition, it is assumed that the decontamination process is more energy-intensive than size reduction and direct packaging of waste. Based on these considerations, the value assessment panel concluded that the overall environmental impact of the COREMIX process was slightly worse than that of the baseline waste management route, and neutral if decontamination led to free release and recycling of metals.

On the other hand, attendees highlighted that process optimisation was likely to result in a 40% decrease in energy and material requirements.

Having reviewed the preliminary figures and conclusions drawn by the University of Manchester, the LCA calculations presented in PREDIS D2.9 [20] clearly show that metal recycling significantly outweighs all the other disbenefits. The overall impact of manufacturing 300 tonnes of Inconel as assumed under the baseline assumptions is significantly more detrimental than decontaminating and recycling the same amount of metal².

*Overall, the value assessment concludes that, based on **preliminary** evidence produced by the LCA process, the environmental impact of using the COREMIX process is **much better** than under baseline assumptions. This is in contradiction with the conclusions drawn by the panel, which only considered partial evidence from the LCA calculations.*

5.3.3 Disposability and Long Term Safety

Disposal of activated and contaminated metallic ILW to a GDF, as assumed in the baseline, has been demonstrated, in general, to meet Waste Acceptance Criteria (WAC). Under the same assumptions, only “housekeeping waste³” and cutting fluid will be generated as secondary waste during the cutting and conditioning stages.

Disposal of decontaminated PWR steam generators as VLLW to surface to near-surface facilities has been demonstrated in France [17]. The panel discussed the characterisation requirements for disposal as VLLW or for clearance, which are likely to be more onerous than waste package measurements required for disposal to a GDF. In addition, during and following decontamination using COREMIX, most of the radioactivity is accumulated in sludge resulting from the precipitation step, with the remaining trace amounts captured by Ion Exchange resins (IEX). Decontamination of one square metre results in approximately 0.22 kg of sludge [21]. The amount of secondary waste

² These conclusions are based on preliminary results provided by the UoM, which will be published in PREDIS D2.9 [20]. Exact figures are excluded from this report to prevent conflicts with thesis publication dates.

³ Comprising, for instance, Personal Protective Equipment (PPE) and sacrificial mixing equipment.

increases with the number of decontamination cycles, which is a weakness of the “full clearance” route. Disposal of IEX resins can be problematic, although the COREMIX-HP process results in approximately 90% less IEX resins compared to the original CORD process. Polymer encapsulation is currently used by EDF (using the MERCURE mobile encapsulation plant) in France for IEX resin management, reducing further the impact of this issue.

Cutting fluid and other equipment used during size reduction operations will carry less activity than under baseline assumptions, making them easier to handle, and potentially allowing for recycling or diversion from disposal. However, equipment associated with the decontamination loop is likely to become slightly contaminated and/or activated. Two related scenarios were discussed by the attendees:

- If existing plant equipment can be re-used for the decontamination process, such as in Post Operational Clean Out (POCO), then there will be little to no additional radioactive waste associated with the COREMIX process. It is even likely that some of the associated systems, structures and components will benefit from the process and see their radioactivity reduced.
- If plant equipment cannot be re-used and a dedicated COREMIX loop must be set-up, then such equipment will become radioactive waste at the end of the process.

*In terms of disposability, the value assessment panel concluded that the COREMIX process is **slightly worse** than the baseline route. Diversion from geological disposal being accounted for under the environmental criteria, generation of spent IEX resins and sludge, together with the potential waste arisings from the decontamination loop were deemed a weakness of the COREMIX process. This is mitigated by the relative ease of managing sludge, and by the anticipated low activity levels of other secondary waste.*

5.3.4 Implementation

The attendees recognised the constraints posed by working in radiologically controlled areas, which may result in personnel rotation and limitations to the number of hours worked to reduce exposure to ionising radiations. Such constraints are likely to be applicable under the baseline assumptions but not during size reduction activities following decontamination.

The timescales necessary to achieve partial and full (i.e. down to clearance levels) decontamination were discussed. Each cycle takes 24 hours, with a further 24 to 36 hours required for acid destruction and metal ions precipitation [19]. Three cycles could therefore be undertaken within a week, with full decontamination achieved in twice that time (a further rinsing cycle is usually required and is assumed to last for 24 hours). It was deemed that such timescales would not negatively impact national or site waste management strategies. On the contrary, by enabling prompt decommissioning, decontamination using the COREMIX process is likely to have a positive impact on national and site decommissioning and waste management strategies.

The Technical Readiness Level (TRL) of the COREMIX technology was discussed. Its sibling, the CORD process, has a TRL of 9, while the TRL quoted for COREMIX is 2 to 3, mainly due to the latter “-HP” steps (related to precipitation of secondary waste) which are being developed under PREDIS. Although apparently significant, the difference in TRL was deemed to be only slightly disadvantageous to the COREMIX process since industrialisation of similar chemical processes has been achieved and demonstrated, including in CORD. Therefore, the panel concluded that

progression up the TRL scale was likely to be relatively quick, provided that adequate and continuous funding was provided for its development.

*Implementation of the COREMIX process was considered to be **better**, or easier, than that of the baseline approach. The lower TRL was easily compensated for by the removal of constraints associated with size reduction of ILW metal. Giving national Waste Management Organisations and individual sites the option for prompt decommissioning was also deemed to be a significant strength of the decontamination approach.*

5.3.5 Cost

During the workshop, the panel agreed that costs associated with secondary waste management were likely to be of the same order of magnitude between the baseline and variant scenarios. It was further acknowledged that the cost of the decontamination reagents was likely to be dwarfed by the financial implications of geological disposal or steel recycling. While initial cost assessments were discussed at the workshop, detailed Life Cycle Costing (LCC) data will be presented in PREDIS D2.9 [20] and are not included in this report.

The cost of deep geological disposal is estimated at £5000/m³ [**Error! Bookmark not defined.**], with near-surface disposal costing ten times less [22]. A comparison of the cost implications of recycling 300 tonnes of Inconel 690 (density 8.19 t/m³ [23]) against geological disposal with an assumed waste loading for disposal of 25%vol demonstrated significant cost benefit associated with recycling, assuming that metal is at market value. The cost benefit is approximately 10 times greater than the cost of disposal of the same volume of waste.

Cost data related to the costs of decontamination using the COREMIX process itself are subject to further process optimisation. However, the cost per square metre of undertaking three decontamination cycles can be approximated as £500/m². For a typical steam generator with a surface area for decontamination of 4700 m², this results in a total decontamination cost of approximately £4.7 million (half that sum for decontamination to VLLW levels). When the decontamination costs are subtracted from the cost benefit associated with recycling of the steel, the financial benefit remains significant.

*Overall, the value assessment panel agreed that decontamination using the COREMIX process is **much cheaper** than managing waste with the baseline approach. This is substantiated by process, material, and disposal cost data gathered ahead of, and during the value assessment workshop.*

5.4 Discussion of the Economic and Environmental Impacts of Aspigels and EASD

Two gels (EASD and Aspigel, developed within PREDIS by NNL and the CEA, respectively) were evaluated for the decontamination of ILW hot cells. It is assumed that the metal obtained after decontamination is categorised as VLLW and is packaged in ISO containers for disposal at a near-surface facility (without cementation). Process byproducts (e.g. dried gel) are assumed to be borderline ILW/LLW and will be cemented and disposed of at a GDF.

These technologies are assessed against the same baseline assumptions (size reduction of contaminated metal followed by cementation and disposal at a GDF) as those used for the assessment of the COREMIX process. Both gels were assessed together, with meeting participants highlighting differences where relevant. Differences in the intended scope of application of these two gels were highlighted and acknowledged. Aspigel is intended for decontamination of entire planar

areas, whilst EASD is developed for hot spot removal. The value assessment tables are presented in Appendix 2.

The University of Manchester used the LCA model developed within PREDIS WP2 to assess the environmental performance of these two processes [20]. The hot cell cladding was assumed to be 0.48 m thick, with a total surface area of 163 m², resulting in a total volume of 78.24 m³. Assuming a standard stainless steel 316 density of 8 t/m³ [24], this amounts to 625.9 tonnes of metal requiring treatment.

A set of common assumptions was agreed during discussion of the cross cutting criterion. In particular, it was agreed that conclusions would be drawn based on the assumptions that:

- Gels are applied homogeneously on the metallic surface.
- Contamination is homogeneously distributed on the metallic surface.
- The cost implications of diverting waste away from a GDF (to surface or near-surface disposal) are the same as those highlighted in Section 5.3.

5.4.1 Operational Safety

Treatment under baseline assumptions comprises size reduction activities necessary to render the hot cells into metallic waste suitable for conditioning. Such activities are assumed to be undertaken in an active environment, with the controls and restrictions associated with radiologically controlled areas (such as controlled or supervised areas, as defined in the Basic Safety Standards Directive [18]). Metal cutting activities undertaken on metal with intermediate levels of radioactivity incur significant radiological and conventional risks to the operators.

Characterisation is an essential step in both the variant and baseline scenarios; to demonstrate compliance with waste package specifications for GDF disposal for the latter, and to demonstrate compliance with VLLW Waste Acceptance Criteria for the former.

Gel decontamination reduces or removes the need for metal cutting activities in an active environment since size reduction can be undertaken following full decontamination or hot spot removal. In addition, gels can be sprayed onto the surface to be decontaminated, further reducing exposure by allowing operators to maintain some distance from the active surfaces. However, EASD requires the application of electrodes directly onto the surface to be decontaminated, partially negating the benefit highlighted above.

Research partners reported that, as anticipated, some level of activity concentration was observed, requiring dried gel residues to be handled as borderline LLW/ILW or as ILW. However, meeting participants agreed that this was compensated for by the significant reduction in waste quantity and complexity; they reported that dried gel volumes were of the order of magnitude of millilitres and were easily removed by vacuuming, packaged and conditioned for disposal.

*Overall, the assessment panel concluded that, based on the evidence assembled, operational safety was **better** when using the gels than under baseline assumptions. The reduction in radiological risk that results from undertaking size reduction after decontamination outweighs the risks associated with manipulation of low volumes of high specific activity secondary waste.*

5.4.2 Environmental Impact

Discussions around the environmental impact of gels focused on their manufacture and the impact of their formulation. The Aspigel formulation includes cerium nitrate, which was reported as being the principal contributor to environmental damage from this gel's manufacture. It was agreed that the environmental impact of EASD was lower, although benefits arising from the absence of cerium nitrate in the gel formulation are partly negated by the need for electrodes, power packs, and control

panels. The likelihood of electrode contamination was reported as low, and the gel's capacity to absorb contamination was reported as high, resulting in an efficient process and in small amounts of secondary waste. Process energy requirements were reported to be of a similar order of magnitude between gel decontamination and waste management under baseline assumptions.

Similar remarks to those made in Section 5.3.2 can be made with regards to gel decontamination, and as a result, the above discussion is only valid as long as metal recycling following gel decontamination is excluded (as is the case in these specific scenarios). Preliminary results from LCA modelling indicate that the environmental benefit of recycling metal (vs. smelting from raw ore) significantly outweighs all other disbenefits⁴.

*Overall, the assessment panel concluded that, based on the evidence assembled, the environmental impact of decontamination was **slightly worse** than that of the baseline scenario, based on the environmental impacts associated with gel manufacture. However, based on preliminary evidence produced by the LCA process, such a conclusion is reversed if decontaminated metals are recycled, either directly or following a period of decay storage.*

5.4.3 Disposability and Long Term Safety

Discussions around disposability and long-term safety included primary and secondary waste after it was recognised that focusing solely on secondary waste would bias the assessment. Primary waste was assumed to meet the relevant WAC in both scenarios; however, gel decontamination leads to significantly lower volumes of ILW requiring disposal. On the other hand, this process also results in increased secondary waste quantities (e.g. dried gel removal equipment), which might need to be managed as ILW.

Storage needs for the resulting waste (if disposal capacity is not available immediately) were discussed by the attendees, who concluded that the variant scenario required a smaller storage capacity compared with the baseline.

*Overall, the assessment panel concluded that, based on the evidence assembled on disposability and long term safety, the impact of implementing gel decontamination is **broadly similar to slightly worse** than that of implementing the baseline approach.*

5.4.4 Implementation

Research partners reported, ahead of and during the meeting, that demonstration trials had been undertaken at full scale (Aspigel), and on small coupon and cylindrical samples (EASD). Decontamination timescales are similar to those reported for COREMIX, with gel-drying occurring within 24 hours, and gel application being accelerated by spraying. When compared with the time required for size reduction in a radiologically controlled environment, potentially delayed by the need to manage doses to operators, the attendees agreed that gel decontamination was slightly better. This was further substantiated by the opportunity for prompt decommissioning that gel decontamination offers, thus opening options for waste management and enabling more flexible national and site-specific waste management and decommissioning strategies.

Diversion of waste away from geological disposal is also an advantage in terms of national strategy, since reducing the footprint of a GDF is likely to reduce the overall cost associated with radioactive waste management and increase its public acceptability.

⁴ The exact figure is calculated in a draft UoM report and will be included in Deliverable D2.9 [20]. It is excluded from this report to prevent conflicts with thesis publication dates.

TRLs are broadly similar between the variant and baseline scenarios, with TRLs of 7 and 9 for EASD and Aspigel, respectively. While demonstration in an active environment is still required for EASD, the panel concluded that progression up the TRL scale was likely to be relatively quick, if funding was provided for the active demonstration trials and any further development needed to reach TRL 9.

*Overall, the attendees concluded that, based on the evidence assembled and panel discussions, gel decontamination represents a **better and easier** option than the baseline approach, by enabling prompt decommissioning, diverting waste away from geological disposal, and potentially decreasing decommissioning timescales. Further development remains necessary for the EASD gel.*

5.4.5 Cost

The attendees acknowledged that additional costs associated with the decontamination gels and equipment were dwarfed by the cost savings achieved by diverting waste away from deep geological disposal. This is illustrated by the calculations below, which assume that the cost of deep geological disposal is estimated at £5000/m³ or 5910€/m³ [Error! Bookmark not defined.], with near-surface disposal costing ten times less.

Based on the assumptions highlighted at the beginning of this section, deep geological disposal of 78 m³ of steel would therefore cost approximately £250,000 more than near-surface disposal. Research partners reported that gel decontamination using Aspigel gave rise to up to 0.2 kg of dried gel per square metre of treated metal [25]. Treatment of 163 m² of metal would thus result in 32.6 kg of dried gel (0.01 m³, based on a dried gel density of 2 to 3 g/cm³ [25]), potentially ILW and requiring disposal in a GDF. Dried gel quantities arising from hot spot decontamination using EASD were not measured but are anticipated to fall within a similar range [26]. Due to the reduction in ILW volume achieved by decontamination, the impact of dried gel disposal on the overall waste management cost is therefore negligible.

*Overall, the assessment panel concluded that, based on the evidence assembled on costs, metallic waste management via gel decontamination is **much cheaper** than under baseline assumptions. This was substantiated by disposal cost data and discussions, with the panel in agreement that the additional cost of decontamination gel and equipment is of a much smaller scale than that saved by diverting waste from geological to near-surface disposal.*

5.5 Economic and Environmental Impact Assessment Closing Remarks

The above conclusions were drawn area by area, recognising that no overall rating should be attributed. Instead, each organisation and / or End-User might find it useful to individualise the results by applying weighting factors that reflect national priorities.

Results from the assessment of the COREMIX-HP and gel decontamination processes are illustrated in Figure 7 to Figure 10.

Illustrative “safety-focused” and “cost-focused” weightings have been applied and can be visualised in Figure 8 and Figure 10, showing how individual End-Users can exploit the value assessment results and tailor them to reflect their priorities. In those instances, a total of 10 “points” were distributed between the criteria. Safety-related (cost-related, respectively) criteria were scored highly, whilst other criteria were either attributed a low score or a null score.

Figure 7: Presentation of the COREMIX-HP Value Assessment Outcomes – Neutral Weighting

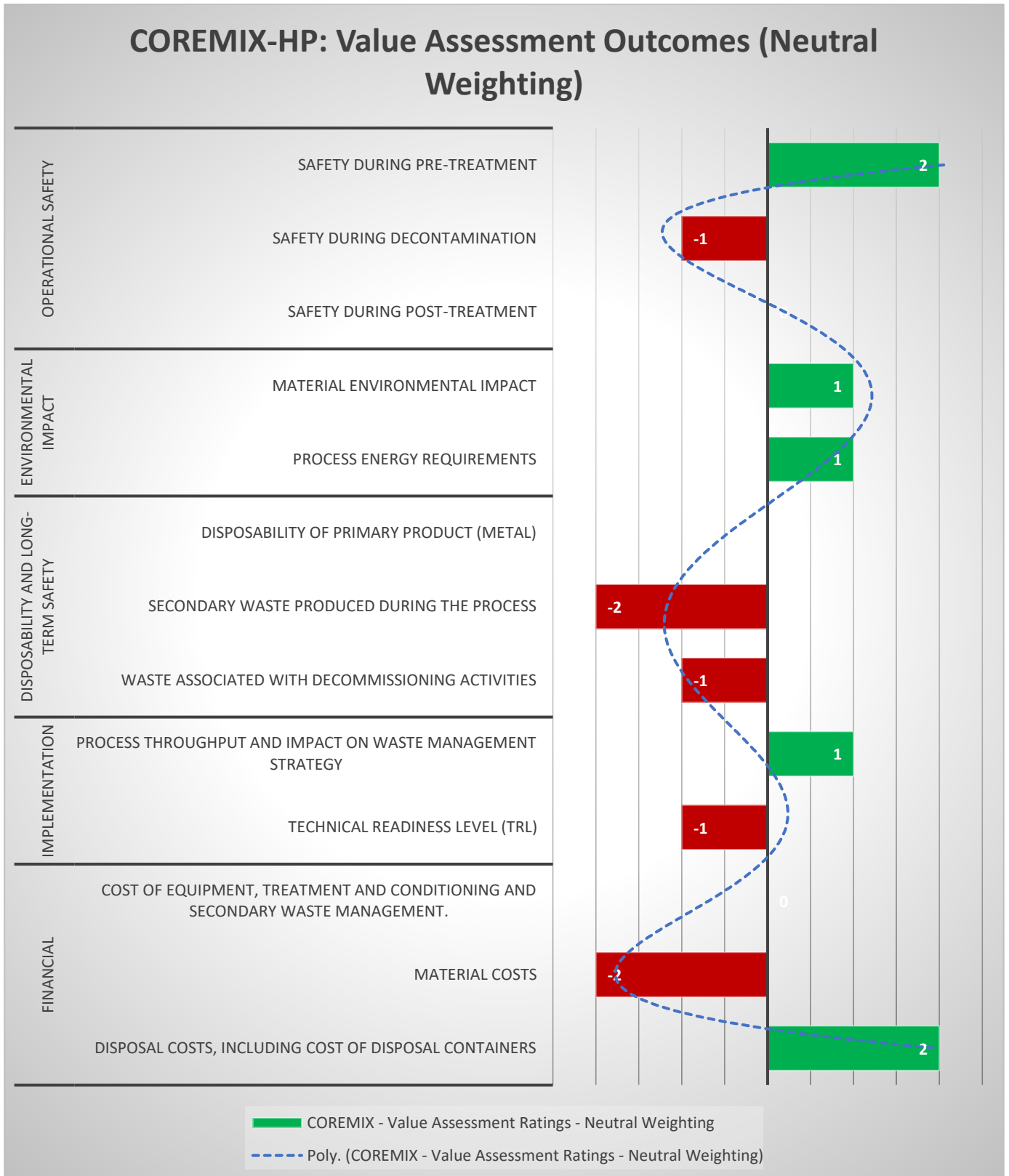


Figure 8: Presentation of the COREMIX-HP Value Assessment Outcomes – Illustrative Safety-Focused Weighting

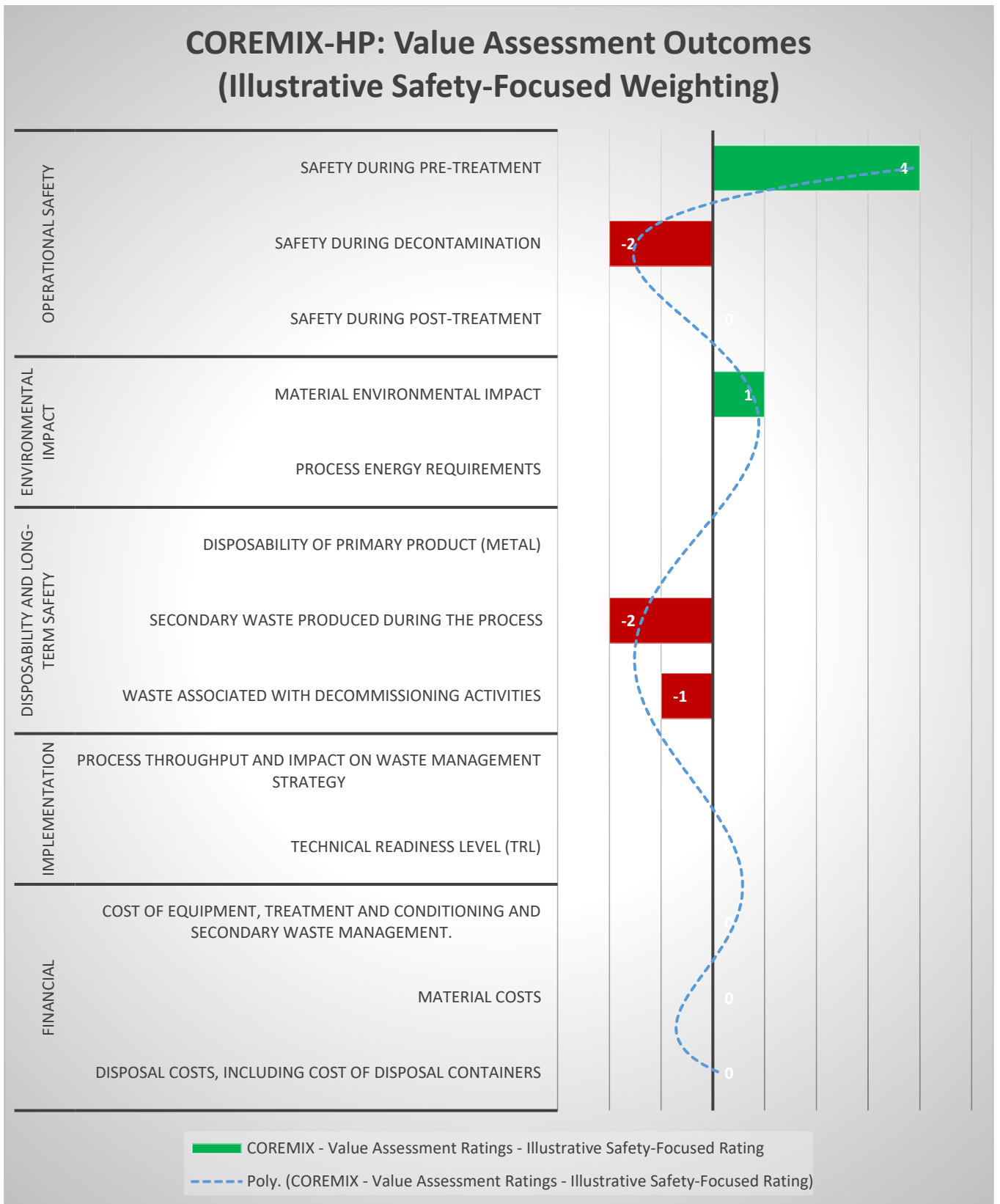


Figure 9: Presentation of the Decontamination Gels Value Assessment Outcomes – Neutral Weighting

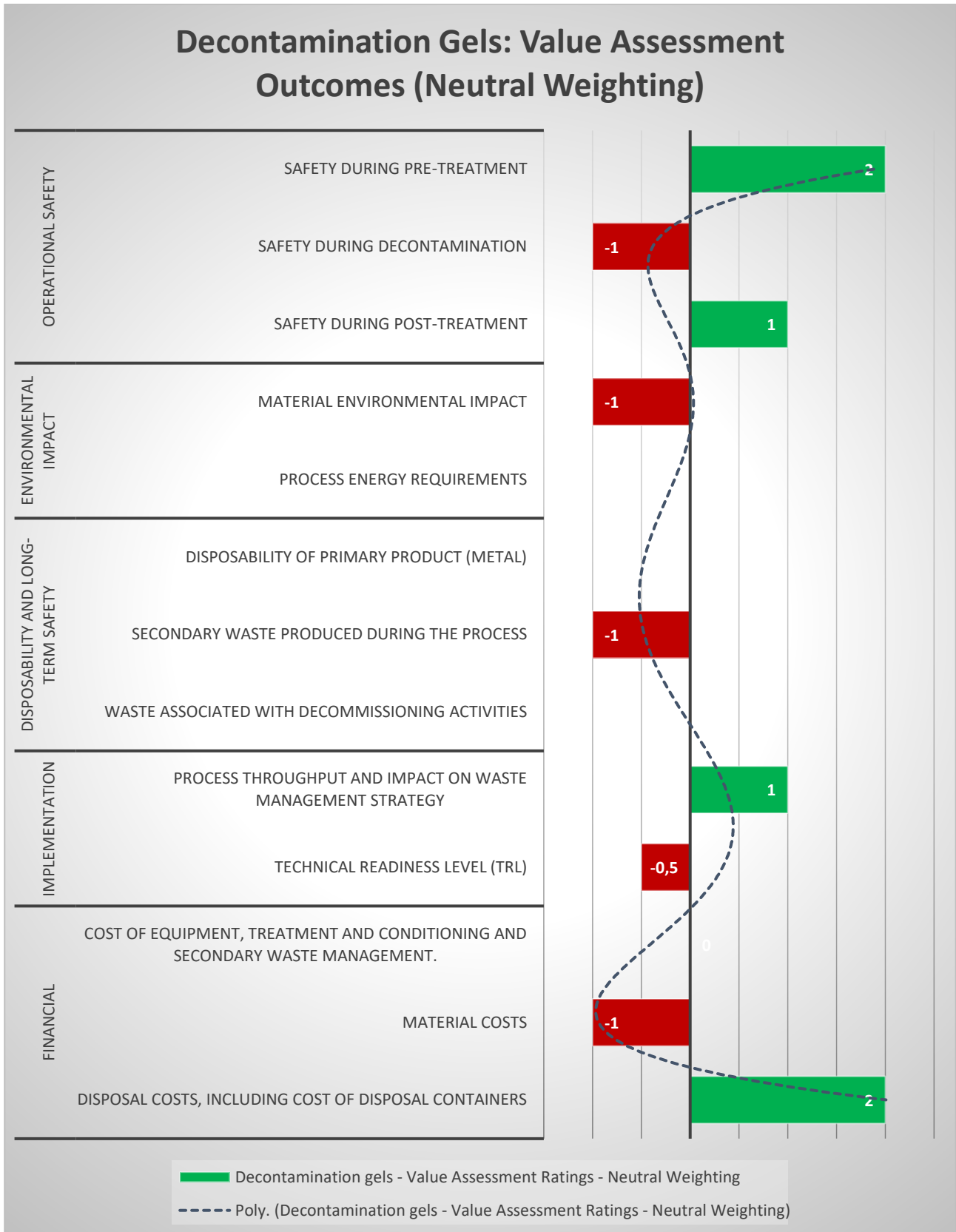
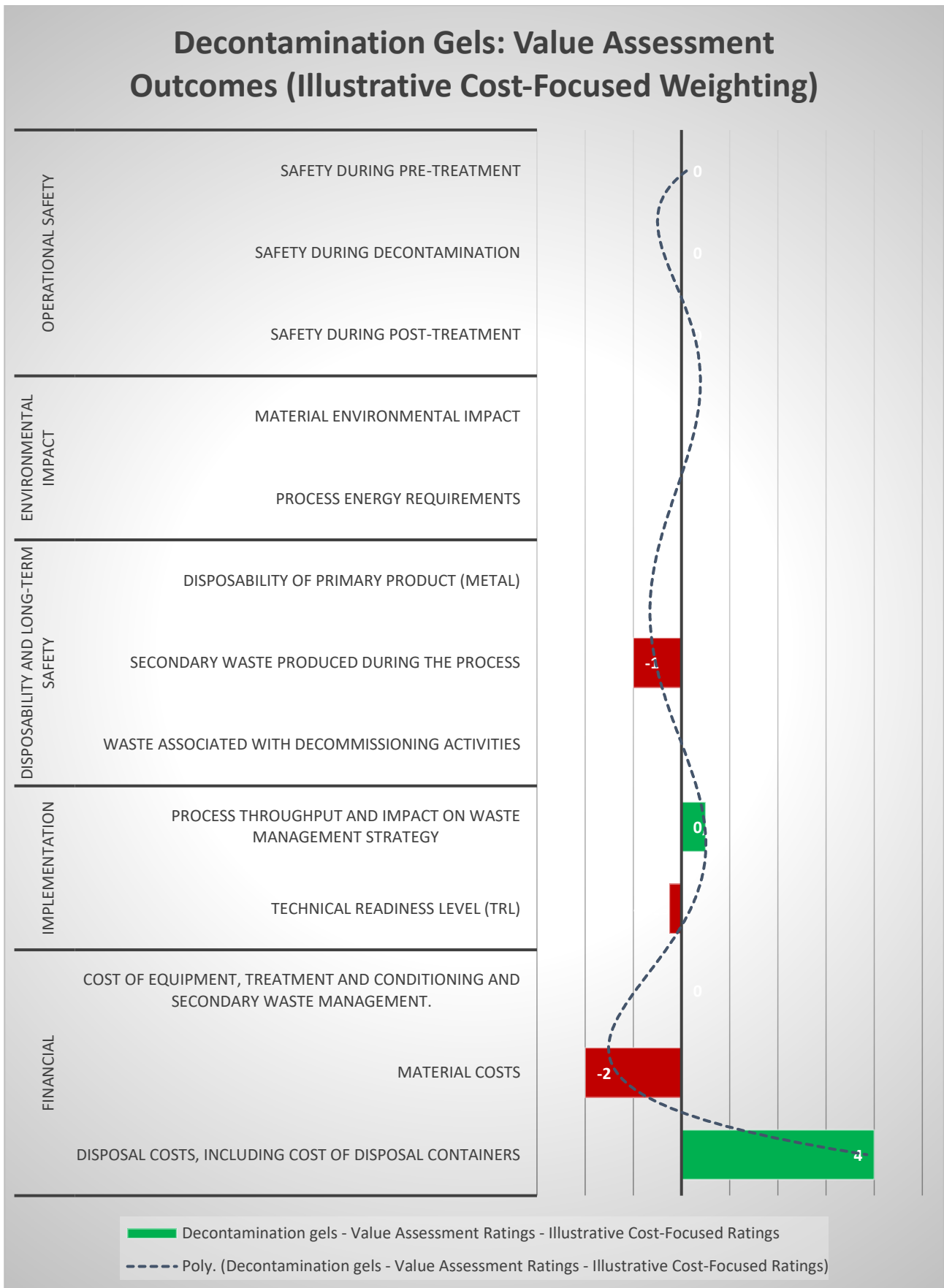


Figure 10: Presentation of the Decontamination Gels Value Assessment Outcomes – Illustrative Cost-Focused Weighting



6 Summary and Conclusions

The metallic waste inventory produced at the start of PREDIS WP4 gave a measure of the current and future scale of the challenge associated with managing this type of waste. Some waste streams can be managed via existing treatment and conditioning routes, whilst others do not have a credible management route to enable recycling or disposal. The first part of Deliverable 4.2 is dedicated to decision-makers and waste producers; the datasheets provided offer an extensive coverage of the mechanical, chemical and thermal treatment routes, and show the variety of technologies available on the market or in development (such as PIVIC). Non-nuclear melting technologies are also detailed in this report (such as rotary furnace or Electric Arc Furnace Melting).

Challenges associated with each waste stream and facility can be matched to one, or a combination of technologies, but each technology's potential will need to be assessed on a case-by-case basis.

Three decontamination technologies were further studied and developed in PREDIS WP4:

- Decontamination gels:
 - Aspigel.
 - Electrolytically Assisted Surface Decontamination (EASD) gels.
- COREMIX-HP.

User feedback gathered at the start of the project [27] showed that surveyed organisations expected improvements in one or more of the following three priority areas:

- Volume reduction.
- Cost savings.
- Development of a management route when none exists.

The economic, environmental and safety impacts of the three technologies developed in WP4 were evaluated against those, and a wider range of criteria, to assess whether the project was successful and beneficial to End-Users. The value assessment process developed in THERAMIN was applied to provide a rigorous and systematic impact assessment, against a baseline, representing current, or planned waste management practices.

The conclusions were unequivocal. Both COREMIX and gel decontamination were found to lead to significant cost savings, driven by waste volume reduction, and metal recycling, made possible in some instances by surface decontamination. Both avenues present neutral to improved environmental outcomes when compared against the current option, which is size reduction and disposal as ILW. Secondary waste management (e.g. spent ion exchange resins generated by the COREMIX process) and disposal were identified as areas requiring further research and development, although no unsurmountable issues were identified.

Some of the waste streams identified in the inventory do not currently have a management route; the approaches developed in PREDIS WP4 can demonstrably offer solutions to treat and condition these waste streams, whilst reducing waste volumes and costs compared with conventional approaches. A forward work programme to address uncertainties associated with the disposability of some of the secondary wastes is proposed under EURAD-2.

APPENDIX 1: VALUE ASSESSMENT (VA) CRITERIA: BOUNDARIES, EXCLUSIONS AND RATIONALE

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages ⁵
Cross-cutting	Material reuse and recycling	Application of the waste hierarchy. Quantities of material diverted from disposal (kg or m ³)	Focused on metal recycling and on the application of the waste hierarchy to steel. Other impacts on the use of raw materials (e.g. cement quantities) are accounted for under “environmental impact” and “financial considerations”.	One of the main drivers behind metal decontamination is to allow re-use and / or recycling. This criterion is included as “cross-cutting” as it impacts several areas, such as environmental impact (change in the use of raw materials) and financial (recycling instead of disposal, or near-surface disposal instead of geological disposal). The aim is to elicit discussions and gather inputs under this cross-cutting criterion. However, no rating is assigned to the cross-cutting criterion as such: its formal impact in terms of Value Assessment is accounted for through the individual criteria that are impacted.	All
Operational safety	Facility construction and decommissioning	Size of the facility. Recorded Health and Safety (H&S) accidents during construction. Judgement on facility complexity.	Excluded from this assessment.	The variant technologies are in-situ processes, which do not require additional facilities compared to the baseline. Cementation facilities are needed in both the baseline and some variant scenarios for secondary waste conditioning. Therefore, this criterion was not judged to be a differentiator.	NA
	Safety during pre-treatment	Dose to workers associated with installation of equipment, size reduction activities, waste handling and packaging. Ease of providing shielding during operations.	Includes radiological and conventional safety.	Size reduction of metallic wastes is required for the baseline (cementation). This differentiates from the in-situ processes studied in PREDIS. Therefore, this criterion is included in the VA.	Pre-treatment
	Safety during decontamination	Shielding requirements. Operator dose rates. Known or anticipated operational issues. Number of decontamination cycles. Number of packages (waste loading).	Includes radiological and conventional safety. Excludes disposability considerations (dedicated set of criteria below).	In-situ decontamination and size reduction/removal of contaminated metals are relevant and differentiating between the baseline and the variant technologies. The differences between the baseline and variant scenarios are significant (chemical risk, time of treatment). Therefore, this criterion is deemed differentiating and is included in the VA.	Treatment and conditioning (considered as one).
	Safety during post-treatment / conditioning Safety demonstration requirements	Dose to workers, chemical safety of handling waste and cement powders, any manual handling operations.	Includes radiological and conventional safety. Excludes disposability considerations (dedicated set of criteria below).	Regulatory requirements in terms of permitting and/or licensing play a significant role in the emergence and implementation of novel technologies. The ability of the variant scenarios to meet regulatory requirements, and the ability of facility operators to assemble the safety demonstration are therefore deemed differentiating. Such demonstrations are necessary for new facilities and processes. Safety during post-treatment and conditioning is a differentiator, due to the presence of various chemical products in the variant scenarios. Therefore, this criterion is included in the VA.	Treatment and conditioning (considered as one).
Environmental impacts	Material Requirements	Equipment/facilities required Sacrificial equipment used Material/chemical inputs used	Includes the environmental impact (including energy use) of material manufacture, for all materials feeding into the process. Excludes cost considerations (see “financial”).	The environmental impact of material manufacture is calculated in the LCA and is a differentiator of particular relevance when considering the potential benefits or weaknesses of the variant scenarios. Therefore, this criterion is included in the VA.	Treatment and conditioning (considered as one).

⁵ Considerations around the impact on planning activities are included within the respective waste management steps and are not detailed separately. Treatment and conditioning are considered as one to allow comparison between the baseline and the variant scenarios.

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages ⁵
	Process energy requirements	<p>Calculated (via Life Cycle Analysis or LCA) process energy requirements.</p> <p>Number of waste packages (waste loading).</p>	<p>Limited to the energy requirements of the process only.</p> <p>Excluding transport.</p> <p>Excludes the energy that would potentially be used to manufacture materials, vs. recycling (this is accounted for in "Material environmental impact").</p>	<p>Process energy requirements are calculated in the LCA and are a differentiator of particular relevance when considering the potential benefits or weaknesses of the variant scenarios. Therefore, this criterion is included in the VA.</p> <p>Transport is excluded to remove any dependency related to facility location.</p>	<p>Pre-treatment</p> <p>Treatment and conditioning (considered as one).</p>
Disposability / long-term safety	Secondary waste produced during the process	<p>Type and quantity of secondary waste.</p> <p>Known and/or existing management routes for secondary waste, including its disposability.</p>	<p>Includes interim management, existing disposability assessments and regulatory approvals, as well as existing or planned disposal routes.</p>	<p>The ease of and technological readiness for managing secondary waste is an important factor in evaluating the viability of any new waste management technology as well as the decommissioning of the treatment facility/equipment. This criterion is therefore included in the VA.</p>	<p>Treatment and conditioning (considered as one).</p> <p>Storage and disposal</p> <p>Decommissioning</p>
	Disposability of final waste product.	<p>Existing disposability assessments.</p> <p>Known or anticipated issues with waste product characteristics.</p>	<p>Includes disposal to surface and near-surface facilities.</p> <p>Includes disposal to geological disposal facilities (baseline only).</p>	<p>Disposability of the treated metallic waste is already established (as Very Low Level Waste (VLLW), or via recycling routes).</p> <p>Disposability of the secondary waste is included in the previous criterion.</p> <p>This criterion is therefore excluded from the VA.</p>	<p>Storage and disposal</p>
	Waste associated with decommissioning activities	<p>Volume and activity of equipment required for decontamination</p>	<p>Includes interim management, existing disposability assessments and regulatory approvals.</p>	<p>Waste arising from decommissioning of the decontamination processes is addressed under "secondary waste management". The impact on any nuclear facility's decommissioning plans are addressed under "implementation".</p> <p>This criterion is therefore included on a case by case basis.</p>	<p>Decommissioning</p>
Implementation	Process throughput and impact on waste management strategy	<p>Full-scale facility throughput (m³ of waste processed per unit time).</p> <p>Experimental facility throughput and estimated ease of scale-up.</p> <p>Inventory of waste for treatment and conditioning.</p> <p>Other implementation considerations (e.g. anticipated issues during scale-up, throughput-limiting steps).</p>	<p>Excludes transport considerations.</p> <p>Excludes TRL considerations (accounted for in dedicated criterion).</p>	<p>Large-scale strategic impact (e.g. route availability,) and availability of new management routes make this a differentiating criterion.</p> <p>Process throughput is also a differentiator.</p> <p>Therefore, this criterion is included in the VA.</p>	<p>Pre-treatment</p> <p>Treatment and conditioning (considered as one).</p> <p>Storage and disposal</p>
	Technical Readiness Level (TRL)	<p>TRL (1-9).</p>	<p>N/A</p>	<p>TRL is an internationally recognised and accepted way of measuring the technical readiness of a technology. TRL levels are well documented and are used within EC-projects to evaluate technologies and progress in research and development activities.</p> <p>Therefore, this criterion is included in the VA.</p>	<p>Treatment and conditioning (considered as one).</p>
Financial	Cost of facility and of treatment and conditioning and cost of secondary waste management.	<p>Construction cost.</p> <p>Design cost.</p> <p>Decommissioning cost.</p> <p>Cost per m³ of waste processed.</p> <p>Waste loading.</p> <p>Cost of secondary waste management per m³ of waste</p>	<p>Including construction and decommissioning costs if available.</p> <p>Including treatment, conditioning, and disposal of secondary waste.</p> <p>Excluding transport.</p> <p>Excluding storage.</p>	<p>The cost of building, decommissioning, and operating facilities is a significant driver in implementing technical changes. Equipment costs are added to yield the cost of waste processing, per unit volume or mass or surface area. Such cost reductions are of particular importance to member states and to the End-Users and are calculated by the LCC.</p> <p>Therefore, this criterion is included in the VA.</p>	<p>Pre-treatment</p> <p>Treatment and conditioning (considered as one).</p> <p>Storage and disposal</p>

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages ⁵
	Material costs	Calculated cost of materials (via Life Cycle Costing or LCC).	Including costs of sacrificial drums. Including costs of chemical reagents. Excluding transport costs.	Equipment costs are accounted for under the criterion above, but the cost of chemical reagents and other consumables are accounted for in this criterion. Therefore, this criterion is included in the VA.	Treatment Conditioning
	Disposal costs, including cost of disposal containers	Cost of disposal containers. Total volume of waste to be disposed of (waste loading).	Excluding transport. Excluding storage. Including secondary waste.	Disposal costs, and the cost of associated facilities play an important role in decision making related to waste management strategies. Therefore, this criterion is included in the VA.	Storage and disposal

APPENDIX 2: VALUE ASSESSMENT TABLES

COREMIX-HP

4.1.1 and 4.1.2 vs 4.1.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		Overall scenario rating versus baseline	
Area	Criterion	Metric examples	Boundaries and exclusions	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Clearance	VLLW
Crosscutting	Reuse of material	Reuse of steel		No reuse	All steel cleared for general reuse 3 cycles for VLLW 6-7 for full clearance	300 t of steel available for reuse.	None	None	None	Crosscutting: no rating assigned	
Operational safety	Safety during pre-treatment	Dose to workers associated with installation of equipment, size reduction activities, waste handling and packaging. Ease of providing shielding during operations.	Includes size reduction. Includes radiological and conventional safety.	Size reduction results in operators doses and comes with its own set of conventional safety risks.	Time to set up the process, some size reduction may also be required if decontamination is not performed <i>in-situ</i> . ⁶ Greater safety implications if a decontamination bath were used instead of a decontamination loop (also applies during decontamination).	Avoids the need for size reduction of radioactive metals with complex geometries, thus reducing radiological and conventional risks.	NA	None	NA	+2	+2
	Safety during decontamination	Shielding requirements. Operator dose rates and cumulative dose (man Sieverts). Known or anticipated operational issues. Number of treatment and conditioning steps. Number of packages (waste loading).	Includes radiological and conventional safety.	No treatment	Time spent in the room to sample, control the composition/pH of the solution, to add decontamination agents to the process and to dismantle it. Handling of decontamination agents. Heating needed.	None	NA	Operational dose from conducting process and conventional risk from handling of chemicals (acidic and oxidising).	NA	-1	-1
	Safety during post-treatment	Dose to workers, chemical safety of handling waste and cement powders, any manual handling operations.	Includes radiological and conventional safety.	Worker operational dose, manual handling operations and handling of cement.	Worker operational dose, manual handling operations, handling of cement, handling of secondary waste.	Safety risk of producing steel reduced (compared to production of steel from ore).	NA	NA	Handling of secondary waste/decontamination agents. Size reduction operations, albeit with reduced radiological risk compared to the baseline.	NA	0

⁶ It is assumed for the rest of this assessment that decontamination is conducted *in situ* and that size reduction occurs after decontamination.

4.1.1 and 4.1.2 vs 4.1.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		Overall scenario rating versus baseline	
Area	Criterion	Metric examples	Boundaries and exclusions	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Clearance	VLLW
Environmental impact	Material Requirements	Equipment/facilities required. Sacrificial equipment used. Material/chemical inputs used.	Includes the environmental impact (including energy use) of material manufacture, for all materials feeding into the process . Includes material reuse and/or recycling.	Personal Protective Equipment (PPE), sacrificial equipment (blades) and cutting fluid. Cement for grouting. No material reuse.	Sacrificial equipment (blades) and cutting fluid (for size reduction of decontaminated metal). PPE, pumps, tools, hoses, valves, tanks. Process chemicals: (values are per m ² for 3 cycles): 1200 L oxalic acid (44 mM) 1200 L KMnO ₄ (15mM) 0.94 L Nitric acid 26 L hydrogen peroxide (0.1M) 4.8 kg solid NaOH (In mass terms 2.87 kg KMnO ₄ 0.24 kg HNO ₃ 4.7 kg H ₂ C ₂ O ₄ .2H ₂ O 86 kg H ₂ O ₂ 4.8 kg NaOH)	Avoids use of grout. Avoids use and excavation of raw ores (if steel is cleared for recycling). Opens the door to recycling within the nuclear industry if VLLW (or recycling following decay storage). The environmental cost of steel production was demonstrated to outweigh that of chemical use in the LCA.	NA	Increased material requirements compared to baseline. This is to be expected given the increased processing burden. Diffusion of tritium into metal may be hard to remove. In such cases, full decontamination requires removal of base metal layers.	NA	+1	0
	Process energy requirements	Calculated (LCA) process energy requirements. Number of waste packages (waste loading).	Limited to the energy requirements of the process only. Excluding transport.	Difficult to assess	<i>Specific energy requirements for this process will be presented in PREDIS D2.9 [20] and are expected to reduce following optimisation.</i> Size reduction is still required albeit for decontaminated steel.	Energy associated with production of virgin steel is avoided.	NA	Higher energy use of process itself.	NA	+1	-1
Impact on disposability / long term safety	Disposability of primary product (metal)	Known and/or existing management routes for primary waste, including its disposability.	Includes interim management, existing disposability assessments and regulatory approvals.	Metal to geological disposal facility (GDF) - meets Waste Acceptance Criteria (WAC).	Metal to free release – meets clearance requirements. Metal to VLLW facility – meets WAC. May be recycled following a period of decay storage.	NA	None	NA	Requires demonstration of activity level via characterisation (possibly including Difficult To Measure (DTM) radionuclides).	0	0
	Secondary waste produced during the process	Type and quantity of secondary waste. Known and/or existing management routes for secondary waste, including its disposability.	Includes interim management, existing disposability assessments and regulatory approvals.	PPE, filters, sacrificial equipment (blades/cutting materials) metal dust(possibly), cutting fluid (mineral oil or similar)	1.04 t of sludge total (0.22 kg/m ²) potentially more for full decontamination PPE, ion exchange resins (IEX), filters Amount of IEX is minimised by use of precipitation method.	None	Avoids use of liquid organics (cutting fluid).	Increased amounts of secondary waste which require processing.	Increased amounts of secondary waste for disposal. IEX can, sometimes, be harder to dispose of (polymer encapsulation option).	-2	-1

4.1.1 and 4.1.2 vs 4.1.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		Overall scenario rating versus baseline	
Area	Criterion	Metric examples	Boundaries and exclusions	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Clearance	VLLW
	Waste associated with decommissioning activities	Volume and activity of equipment required for decontamination	Includes interim management, existing disposability assessments and regulatory approvals.	Cutting equipment and auxiliary equipment	Pumps, tools, hoses, valves and tanks (variable depending on facility – ability to use pumps and tanks already installed).	NA	None	NA	Likely increased amounts of contaminated equipment.	-1	-1
Implementation	Process throughput and impact on waste management strategy	<p>Full-scale facility throughput (m³ of waste processed per unit time).</p> <p>Experimental facility throughput and estimated ease of scale-up.</p> <p>Inventory of waste for treatment and conditioning.</p> <p>Other implementation considerations (e.g. anticipated issues during scale-up, throughput-limiting steps).</p>	<p>Excludes transport considerations.</p> <p>Excludes TRL considerations (accounted for in dedicated criterion).</p>	Fully implemented.	<p>Batch process: Takes time to set up process, treatment takes around 48 hours with a few hours to precipitate out (around 6 hours per cycle).</p> <p>Time for secondary waste management (time to dry sludge) – complete drying may not be required as sludge is cemented.</p> <p><i>Further optimisation of process methodology (and thus time) is likely possible.</i></p>	<p>Size reduction occurs after decontamination (may be limits on exposure time of workers for baseline on high dose items which affects rate).</p> <p>Enables prompt decommissioning – may accelerate site decommissioning programme.</p>	NA	None.	NA	+1	This rating may decrease if a large number of cycles is required
	Technical Readiness Level (TRL)	TRL (1-9).	NA	9	2-3	For COREMIX. COREMIX process has a TRL of 9. Novelty of COREMIX is primarily around precipitation method for management of liquid effluents, generating secondary waste.	None	NA	TRL of 2-3 vs. 9.	NA	-1
Financial	Cost of equipment, treatment and conditioning and secondary waste management.	<p>Construction cost.</p> <p>Design cost.</p> <p>Decommissioning cost.</p> <p>Cost per m³ of waste processed.</p> <p>Waste loading.</p> <p>Cost of secondary waste management per m³ of waste</p>	<p>Including construction and decommissioning costs if available.</p> <p>Including treatment, conditioning, and disposal of secondary waste.</p> <p>Excluding transport.</p> <p>Excluding storage.</p>	Done <i>in-situ</i> but equipment is required.	Done <i>in-situ</i> but equipment is required (could possibly be a mobile facility which would further reduce costs). Increased amount of secondary waste generated which requires management and associated infrastructure compared to baseline).	Roughly comparable pricing.	NA	Roughly comparable pricing but more secondary waste.	NA	0	0

4.1.1 and 4.1.2 vs 4.1.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		Overall scenario rating versus baseline	
Area	Criterion	Metric examples	Boundaries and exclusions	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Clearance	VLLW
	Material Costs	Cost of reagents and sacrificial materials per steam generator		Cutting fluid, blades, cement	<p>Per m², for 3 cycles:</p> <p>1200 L oxalic acid (44 mM)</p> <p>1200 L KMnO₄ (15mM)</p> <p>0.94 L Nitric acid (3mM)</p> <p>260 L hydrogen peroxide (0.1M)</p> <p>4.8 kg solid NaOH</p> <p>Noting that reaching clearance levels is expected to require 6-7 cycles.</p> <p>(In mass terms, for 3 cycles</p> <p>2.87 kg KMnO₄</p> <p>0.24 kg HNO₃</p> <p>4.7 kg H₂C₂O₄.2H₂O</p> <p>8.8 kg H₂O₂</p> <p>4.8 kg NaOH)</p> <p><i>Specific costs for each reagent will be presented in PREDIS D2.9 [20].</i></p>	None, pending input from LCC on steel cost.	N/A	Higher costs	N/A	-2	-1
	Disposal costs, including cost of disposal containers	Cost of disposal containers Total volume of waste to be disposed of (waste loading)	Excluding transport. Excluding storage.	Disposal of 300 T of steel (steam generator) (plus secondary wastes)	<p>Clearance of steel but increased amounts of secondary waste and potentially lower waste loadings. Main waste product is sludge (0.22 kg/m² resulting in 1.04 t for a steam generator (300 t with a surface area of 4700 m²).</p> <p>Clearance of steel is counted as a negative cost.</p>	NA	Smaller amounts of waste require storage and disposal. Steel released to market counts as a negative cost (ca. €20/kg for Inconel steel).	NA	None.	+2	+2

Aspigels and EASD Gels

4.2.1 and 4.2.2 vs 4.2.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		Overall scenario rating versus baseline	
Area	Criterion	Metric examples	Boundaries and exclusions	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	CEA Gel	EASD
Crosscutting	Material reuse / application of the waste hierarchy	Amount diverted from disposal. Amount diverted from geological disposal.		Disposal to a GDF.	Disposal costs (orders of magnitude): Geological: hundreds of thousands Near-surface: tens of thousands Surface: hundreds to a thousand.	NA	Less waste to GDF Potentially able to dispose of waste sooner (country dependent).	NA	None	Crosscutting: no rating assigned.	
Operational safety	Safety during pre-treatment	Dose to workers associated with installation of equipment, size reduction activities, waste handling and packaging. Ease of providing shielding during operations.	Includes radiological and conventional safety.	Size reduction involves doses to operations and has an associated conventional safety risk.	No pre-treatment steps. Applied in-situ. Gel can be applied directly.	Avoids need for size reduction prior to decontamination which has radiological safety impacts.	NA	None	NA	+2	+2
	Safety during decontamination	Shielding requirements. Operator dose rates and cumulative dose (man Sieverts). Known or anticipated operational issues. Number of treatment and conditioning steps. Number of packages (waste loading).	Includes radiological and conventional safety.	No treatment	Time spent in the room to apply and remove gel. Handling of decontamination agents (minor), effluent and off gas has conventional safety implications EASD: there is an additional need for the operator to apply an electrode to the surface. Mitigated by technology's target approach (hot spot removal).	None	NA	Operational dose from conducting process and minor conventional risk from handling of chemicals.	NA	-1	-1
	Safety during post-treatment	Dose to workers, chemical safety of handling waste and cement powders, any manual handling operations.	Includes radiological and conventional safety.	Worker operational dose, manual handling operations and handling of cement.	Size reduction operations ⁷ . Worker operational dose, manual handling operations, handling of cement, handling of secondary waste. Radioactive particulates generated by gel – only very small amounts.	Reduced operational dose.	NA	Size reduction, handling of secondary waste/decontamination agents. High(er) activity secondary waste which requires handling and treatment.	NA	+1	+1

⁷ It is assumed that size reduction occurs after decontamination.

4.2.1 and 4.2.2 vs 4.2.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		Overall scenario rating versus baseline	
Area	Criterion	Metric examples	Boundaries and exclusions	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	CEA Gel	EASD
Environmental impact	Material Requirements	Equipment/facilities required. Sacrificial equipment used. Material/chemical inputs used .	Includes the environmental impact (including energy use) of material manufacture, for all materials feeding into the process .	PPE, sacrificial equipment (blades) and cutting fluid .	PPE, sacrificial equipment (blades) and cutting fluid Pumps, tools, hoses, valves, tanks (below values are per m ²) 1 kg of gel 15% HNO ₃ 15% Ce(NO ₃) ₃ 17% Silica 53% H ₂ O	None	NA	Increased processing burden means increased material requirements. Production of cerium nitrate is an intensive process.	NA	-1	-1
	Process energy requirements	Calculated (LCA) process energy requirements. Number of waste packages (waste loading).	Limited to the energy requirements of the process only. Excluding transport.	Energy associated with size reduction	<i>Specific energy requirements for this process will be presented in PREDIS D2.9 [20].</i> Size reduction will be required after decontamination.	None	NA	Energy for size reduction is required in both cases. Additional energy is required for decontamination. Process energy requirements are, however, dwarfed by the environmental impact associated with steel production from raw ore. This is relevant if decontamination leads to recycling, either directly or following decay storage.	NA	0	0
Impact on disposability / long term safety	Disposability of primary product (metal)	Known and/or existing management routes for primary waste, including its disposability.	Includes interim management, existing disposability assessments and regulatory approvals.	Metal to GDF - meets WAC	Meets VLLW facility WAC.	NA	Diversion from Geological disposal.	NA	Need to demonstrate efficacy of decontamination – potentially including DTM radionuclides	0	0
	Secondary waste produced during the process	Type and quantity of secondary waste. Known and/or existing management routes for secondary waste, including its disposability.	Includes interim management, existing disposability assessments and regulatory approvals.	PPE, filters, sacrificial equipment (blades/cutting materials) metal dust(possibly), cutting fluid (mineral oil or similar)	~150-200 g of inorganic solid residue once vacuumed (per m ²) [25] for Aspigel. No mass was determined for EASD gels but 4L of gel in used to treat 1m ² . Water (few L) PPE, filters Size reduction equipment	None	Avoids use of liquid organics (cutting fluid).	Increased amounts of secondary waste that require processing.	Increased amounts of secondary waste for disposal.	-1	-1
	Waste associated with decommissioning activities	Volume and activity of equipment required for decontamination	Includes interim management, existing disposability assessments and regulatory approvals.	Cutting equipment and auxiliary equipment, more storage facilities required (country dependent)	Vacuums and sprayers. Cutting equipment and auxiliary equipment.	Less storage capacity required (country dependent)	None	None	Increased amount of equipment requiring decommissioning (size reduction equipment is also required for variant)	0	0

4.2.1 and 4.2.2 vs 4.2.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		Overall scenario rating versus baseline	
Area	Criterion	Metric examples	Boundaries and exclusions	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	CEA Gel	EASD
Implementation	Process throughput and impact on waste management strategy	<p>Full-scale facility throughput (m³ of waste processed per unit time).</p> <p>Experimental facility throughput and estimated ease of scale-up.</p> <p>Inventory of waste for treatment and conditioning.</p> <p>Other implementation considerations (e.g. anticipated issues during scale-up, throughput-limiting steps).</p>	<p>Excludes transport considerations.</p> <p>Excludes TRL considerations (accounted for in dedicated criterion).</p>	Fully implemented.	<p>Batch process: Few days to set up equipment, spraying (4m²/min), drying (8-24 hours), vacuuming (few m²/min).</p> <p>Size reduction following decontamination.</p>	<p>Size reduction occurs after decontamination (may be limits on exposure time of workers for baseline on high activity items which affects rate).</p> <p>Provides a new management route compared to current position which is often "do nothing / wait".</p> <p>Aligns with national drivers to divert away from GDF.</p>	NA	None.	Need to demonstrate efficacy of decontamination – potentially including DTM radionuclides	+1	+1
	Technical Readiness Level (TRL)	TRL (1-9).	NA	9	9 (CEA), 7 (EASD)	None	NA	TRL of 9 vs. 9 (CEA) TRL of 9 vs. 7 (EASD).	NA	0	-1
Financial	Cost of equipment, treatment and conditioning and secondary waste management.	<p>Construction cost.</p> <p>Design cost.</p> <p>Decommissioning cost.</p> <p>Cost per m³ of waste processed.</p> <p>Waste loading.</p> <p>Cost of secondary waste management per m³ of waste</p>	<p>Including construction and decommissioning costs if available.</p> <p>Including treatment, conditioning, and disposal of secondary waste.</p> <p>Excluding transport.</p> <p>Excluding storage.</p>	Done <i>in-situ</i>	Done <i>in-situ</i>	Size reduction operations of decontaminated metal will be more straightforward and therefore more cost-efficient	NA	Increased equipment costs (order of magnitude hundreds). <p>More secondary waste (very low volumes of ILW), directly cemented (small containers are disposed of together with existing waste streams).</p>	NA	0	0
	Material Costs	Cost of reagents and sacrificial materials per steam generator		Cutting fluid, blades	Not provided but estimated at few hundreds € per kg of gel (which treats 1 m ²)	None	N/A	Higher costs	N/A	-1 (significant scale difference)	-1
	Disposal costs, including cost of disposal containers	<p>Cost of disposal containers</p> <p>Total volume of waste to be disposed of (waste loading)</p>	<p>Excluding transport.</p> <p>Excluding storage.</p>	<p>Disposal of hot cell to GDF (625.9 t of steel or 3.8 t / m²)</p> <p>Disposal of used gel to GDF (around 0.2 kg / m² or 33 kg per hot cell)</p>	<p>Disposal of hot cell to GDF (625.9 t of steel or 3.8 t / m²)</p> <p>Disposal of used gel to GDF (around 0.2 kg / m² or 33 kg per hot cell)</p>	NA	Smaller amounts of waste requiring disposal to GDF.	NA	None.	+2	+2

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