Technologies and processes for the incineration of radioactive waste in a bitumen matrix

CASE STUDY

KP-JRC-015

08/08/2025

Foreword

In 2021, the European Commission (EC) adopted a new proposal for a Council Regulation[1] establishing a dedicated financial programme for decommissioning nuclear facilities and managing radioactive waste. This instrument covers the co-funding of the decommissioning programmes of Bulgaria, Slovakia, and the decommissioning of the Joint Research Centre (JRC). A separate Council Regulation[2] was adopted for the decommissioning programme of Lithuania.

The EC JRC is mandated to foster the spread of decommissioning knowledge across all the European Union Member States and facilitate knowledge sharing arising from implementing the abovementioned decommissioning programmes, funded by the Nuclear Decommissioning Assistance Programme (NDAP).

The decommissioning operators from the NDAP (NDAP Operators) implemented and tested a knowledge management methodology in 2021 through Project ENER/D2/2020-273. Using this methodology, the NDAP Operators can develop Knowledge Products that are currently available to share with other European stakeholders. In addition, this methodology is under implementation in the JRC Nuclear Decommissioning and Waste Management Directorate (NDWMD), which becomes a knowledge generator extracting the knowledge from the ongoing decommissioning activities at the different sites (Geel, Ispra, Karlsruhe, and Petten).

The JRC NDWMD aims to become a Centre of Excellence in nuclear decommissioning knowledge management and to develop a decommissioning knowledge platform which allows exchanging information and building on the best practices in the EU inside the multi-annual financial framework (2021 – 2027) strategy. The operational phase of the project is expected to start in 2024 to develop ties and exchanges among EU stakeholders and to document explicit knowledge and make it available through multi-lateral knowledge transfers on decommissioning and waste management governance issues, managerial best practices, technological challenges, and decommissioning processes at both operational and organisational level, to develop potential EU synergies.

This is a Knowledge Product prepared by the JRC NDWMD.

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[1] Council Regulation (Euratom) 2021/100 of 25 January 2021 establishing a dedicated financial programme for the decommissioning of nuclear facilities and the management of radioactive waste, and repealing Regulation (Euratom) No 1368/2013

[2] Council Regulation (EU) 2021/101 of 25 January 2021 establishing the nuclear decommissioning assistance programme of the Ignalina nuclear power plant in Lithuania and repealing Regulation (EU) No 1369/2013

PRODUCT DESCRIPTION

This document on “Technologies and processes for the incineration of radioactive waste (RAW) in a bitumen matrix” was prepared by a team of experts from the European Commission´s Directorate J´s Nuclear Decommissioning and Waste Management (NDWM) programme at the Joint Research Centre (JRC) Ispra site, based in Italy.

A case study is presented in this report, which aims to assist nuclear operators, in decommissioning and/or waste management projects, to select appropriate waste treatment processes for incineration of waste conditioned in bitumen matrices (bituminised waste) or containing organic materials.

The aforementioned study conveys the details and results of a series of tests on different technologies and processes for the incineration of bituminised waste. And, crucially, how said tests were performed in several incineration plants worldwide as part of a selection procedure for a contract to facilitate the incineration of bituminised waste drums at the Ispra site.

This Knowledge Product (KP) was developed as part of an effort to disseminate and share with all EU Member States the knowledge acquired during the decommissioning and RAW management activities performed with funding under Council Regulation (Euratom) 2021/100.

ABSTRACT

This KP describes a case study, which elaborates a series of performance tests on the incineration of bituminised drums (BDs) performed in several facilities with different technologies and processes. It describes the test procedures, reports the results and analyses the outcomes with respect to the minimum performance criteria initially set by the JRC for the acceptance of the proposed methodology for the allocation of a service contract. It focusses on technical performance and compliance, not on any administrative and financial issues that led to the choice of the operator to whom the contract was awarded.

OBJECTIVE

To describe the pros and cons of different technologies in order to support nuclear operators on the matter of incinerating bituminised waste and/or organic waste. In addition to providing guidance on the evaluation and selection of the most suitable processes based on their requirements.

APPROACH

This document was developed by assimilating useful information from a set of documentation produced during a tendering procedure run by JRC for the assignment of a service contract for incineration of bituminised waste. In the preliminary phase of the tender procedure, the JRC performed a series of incineration tests at various available operator’s plants in order to evaluate the technical performances of six (6) different incineration technologies and processes. This KP describes the methods and summarises the results of the tests.

RESULTS, FINDINGS AND INSIGHTS

The results of the tests were compared with the minimum performance requirements set by JRC. It was not intended, and no effort was made, to make any comparison between or to rank the different methodologies. The JRC does not intend to promote or advertise any of the test processes.

Furthermore, the plants where the tests were performed, and the respective operators, have both been anonymised. In addition to this, only the technologies and processes will be described to avoid disclosing sensitive information.

End users can analyse the performance of technologies and autonomously select those technologies and processes which best fit their requirements and waste typology.

TARGET USERS

As stated above, this report could be useful for any nuclear operators who need to incinerate bituminised waste, as well as other organic waste, not necessarily conditioned in a bitumen matrix.

APPLICATION, VALUE AND USE

This document summarises the experience gathered by the JRC during the tendering process of a service contract for bituminised waste incineration. Such a treatment process is relevant to any nuclear operator managing bituminised waste or, more generally, with organic RAW.

An operator needing to evaluate and select an incineration service for its own needs has to perform its own market survey and technical assessment. This document will help any operator to understand which technologies and processes are available, as well as to estimate how a selected technology might perform, without the need to validate them through new tests.

The act of transferring knowledge from the JRC to other operators can save significant effort in the selection of procedures for the most appropriate treatment methods.

KEYWORDS

Waste management, waste treatment, incineration, volume reduction.

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LIST OF ACRONYMS AND DEFINITIONS

BD	Bituminised Drums
HDPE	High Density Polyethylene
HEPA	High Efficiency Particulate Air (filter)
JRC	Joint Research Centre (of the European Commission)
KM	Knowledge Management
KP	Knowledge Product
ILW	Intermediate Level Waste
LLW	Low Level Waste
NDAP	Nuclear Decommissioning Assistance Programme
NDWM	Nuclear Decommissioning and Waste Management
NPP	Nuclear Power Plant
RAW	Radioactive Waste
VLLW	Very Low-Level Waste
VRF	Volume Reduction Factor
WAC	Waste Acceptance Criteria
WM	Waste Management

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1. BACKGROUND

1.1. Description of the challenges or problem

In the past, bitumen matrices were a common way to condition RAW from very low-level waste (VLLW) up to intermediate level waste (ILW), and are still in use in several countries. The JRC has conditioned and disposed of more than 6000 BDs between the 1960s to the 1980s. These drums were buried in three trenches; the picture on the cover of this report shows the trenches at the time of their filling. The Regulatory Body, through the Italian National Safety Authority (now ISIN) determined that this disposal method is no longer acceptable and asked the JRC to retrieve the BDs. Moreover, the bitumen drums exceed the limits of organic content acceptable at the Italian national final waste repository. The elimination of the waste by the incineration of bitumen matrices is a commonly practiced solution.

Prior to the assignment of a contract for the incineration of the BDs, the JRC performed a series of incineration tests on mock-ups (drums containing waste simulating RAW) of BDs. The tests were carried out at various operating plants in order to evaluate how the different technologies and processes performed. This document describes the methods and the results of the tests.

1.2. Constraints

The test campaign was held several years ago, between March to November of 2014. Nevertheless, a recent study commissioned by the JRC to a consulting company has revealed that the RAW incineration market has not changed significantly since then, so the case studies remain valid at the time of writing and can be used by nuclear operators to analyse and evaluate the current state-of-the-art of the waste incineration methods.

Due to a contractual confidentiality clause, the JRC cannot fully disclose the results of the tests due to commercially sensitive info. Therefore, in addition to the anonymisation of the plants and operators, the outcomes will be provided in qualitative form without full quantitative results. The assessment will only be made with respect to target values set in the technical specifications, described later in section 3.2, and the report does not give any substantiated comparisons among the different technologies.

1.3. Relevance

Waste incineration can positively affect waste management from several points of view: safety, performance and economics. Drums containing bitumen matrices and organic material in general might exceed the maximum level acceptable for the final repository, making disposal infeasible, unless treated by an incineration process. Moreover, bitumen is flammable; a large quantity of bitumen at a waste storage facility might cause difficulties in meeting fire protection standards and goals. Incineration might also be suitable for treatment of organic liquid waste, either in liquid form or after solidification (for instance through polymerisation). In addition to safety issues, incineration of any organic waste will certainly bring advantages in terms of significant volume reduction.

Since the final disposal costs are somewhat proportional to the waste volume, treatment by incineration is known to significantly reduce disposal costs in some instances. However, it should be noted that a cost-benefit analysis is required to evaluate the reduction of disposal costs versus the treatment costs. An analysis performed by the JRC evidenced a clear economic advantage for incineration, at least for the market conditions at that time and place. The experience gathered in this KP was only available in JRC internal documentation. An operator with a requirement to evaluate and select an incineration service for their own needs will have to perform their own market survey and technical assessment. This document will help any operator to understand which technologies and processes are available, as well as to estimate how a selected technology might perform, without the need to validate them through new tests. The act of transferring knowledge from the JRC to other operators can save significant effort in the selection of procedures for the most appropriate treatment methods.

2. SCOPE

This document conveys the details and results of a series of tests on different technologies and processes for the incineration of bituminised waste. It describes the test procedures, reports the results and analyses the outcomes with respect to the minimum performance criteria initially set by the JRC for the acceptance of the proposed methodology for the allocation of a service contract. It focusses on technical performance and compliance, not on any administrative and financial issues that led to the choice of the operator to whom the contract was awarded.

The results of the tests were compared with the minimum performance requirements set by the JRC. It was not intended, and no effort was made, to make any comparison between or to rank the different methodologies. The JRC does not intend to promote or advertise any of the test processes. Furthermore, the plants where the tests were performed, and the respective operators, have both been anonymised. In addition to this, only the technologies and processes will be described to avoid disclosing sensitive information.

End users can analyse the performance of technologies and autonomously select those technologies and processes which best fit their requirements and waste typology.

3. OVERVIEW OF THE CASE STUDIES

3.1. Extent and validity of the pilot tests

The JRC launched the call for tenders in 2012. Six companies/consortia applied, representing the entire market of RAW incineration at that time. The first phase of the call consisted in organising a series of demonstration tests on mock-ups of BDs at the bidders' facilities, according to minimum expected performance criteria set by JRC in a technical specification document [1]. All tests took place between March and November 2014.

It is only natural for readers to ponder whether the results are still valid today. A study, commissioned by the JRC to a consultancy in 2023, revealed that there were still not any new commercial operators, at least on the European market, offering RAW incineration services. So, from the technological point of view, the pilot scale tests can still be considered representative of the current state-of-the-art. The only perceivable changes that could arise in the future might derive from technical improvements of the plants and processes. Such technical improvements might eventually lead to better results than those provided in the pilot tests.

All six (6) technologies and processes, as well as results on how they performed, are detailed in the following sections. And brief descriptions of the case studies can be seen below:

- The first three (3) case studies involve operators with operational plants based in EU countries.
- The fourth (4th) and fifth (5th) cases refer to plants based in countries outside the EU.
- The sixth (6th) and last case refers to a plant planned at the time of the tests to be built in an EU country but tested on a pilot plant situated outside of the EU. Some special considerations apply to the last case:
    - While the planned plant was never built; the results have been reported for completeness because the proposed technology is interesting and valid. Moreover, there are currently two incineration plants operating in Europe utilising the same technology.
    - Licensing and/or contractual conditions restrict the use of these plants to domestic use only, so they are not currently available on the open market for services to external costumers.

The six (6) case studies are summarised as follows:

Case Study #1

This case study refers to an existing and already operational plant in an EU member state. The method proposed by the potential contractor consisted in a two-phases process. The first step constituted pre-treatment steps which consisted of:

1) opening the drums and separating the material into different streams:
    a. bitumen,
    b. combustible technological waste,
    c. metal and other non-combustible waste.
2) bitumen separation through freezing and fragmentation.

The second step involved treatment processes, which varied depending on the waste materials, such that:

- combustible technological waste was incinerated in the primary furnace,
- bitumen was incinerated in a secondary furnace specifically dedicated to organic material,
- metal was treated in a metal melting plant and, when possible, recycled,
- other non-burnable material (such as stones and glass) would be returned back to the producer as waste,
- secondary waste consisted of conditioned ashes and clinker from the incineration process, as well as non-recyclable metal ingots and refractories from metal melting.

Case Study #2

This case study refers to an existing and already operational plant in an EU member state. The method proposed by the potential contractor consisted in burning the BDs in a furnace with two chambers. The two chambers included: a primary chamber for solid/liquid waste and an afterburning chamber for further processing of gases.

The input capacity of the furnace was insufficient and could not adequately receive the BDs. Therefore, the size of the BDs had to be reduced. The size reduction pre-treatment consisted of:

1) opening and sorting the non-burnable components (sand, stones and metal fragments, to be compacted),
2) dissolution of bitumen with organic solvent,
3) separation, cleaning and compaction of metal components,
4) post-processing and packaging of burnable organic waste for incineration.

The waste from incineration was ashes stored in 200 L drums. The drums storing the ashes were subsequently compacted into 440 L drums, together with metal and other non-burnable waste.

Case Study #3

This case study refers to an existing and already operational plant in an EU member state. The method proposed by the potential contractor is also based on incineration in a furnace. In this case, the potential contractor proposed a pre-treatment process based on heating and melting the BDs to separate the matrix from the content, followed by dry ice blasting for removal of the bitumen residues. The inner compacted drums were subsequently shredded and then incinerated together with the separated bitumen.

Case Study #4

This case study refers to the proposal from an EU potential contractor intending to use an existing plant located in a non-EU country. The proposed treatment process consisted in direct high temperature incineration (without pre-treatment) of drums meeting plant acceptance criteria, or shredding and re-packaging followed by high temperature incineration. The incinerator was not dedicated to RAW only, but a more generic incinerator for industrial hazardous waste. The plant offers the possibility of direct disposal, when the secondary waste complies with local environmental regulation.

Case Study #5

This case study refers to an existing RAW-dedicated plant located in a non-EU country. Several pre-treatment options were tested ranging from simple hole boring to cutting or shredding, and subsequently proceeded by freezing depending on requirements. The simplest pre-treatment method proved to be enough for reaching the required target values, but the more sophisticated ones performed better in terms of volume reduction factor (VRF).

Case Study #6

This case study refers to the proposal from an EU potential contractor who intended to build a plant. The pilot test was conducted in a small pilot plant operating in a non-EU country. This case presents a different technology, i.e. not based on furnace incineration, but rather on a method using a plasma torch. Tests were performed both with direct drum treatment and with preliminary pre-treatment.

3.2. Technical specifications for the pilot tests

The shared objective of the pilot tests was to allow the potential contractors to demonstrate their ability to treat the BDs, so that that JRC could assess the suitability of each contractor to carry out the service contract (1).

For this reason, each contractor was required to perform a test campaign, where mock-ups (simulated BDs) were treated. Each potential contractor took the following requirements into account when carrying out the tests:

- The final objective was to obtain, after the BDs had been treated (and, if necessary, underwent additional pre- and post-treatment), a residual waste in a physical form suitable (i.e. acceptable for qualification) to be stored at the JRC storage facility and eventually to be transferred to the national repository.
- The number of final waste packages should have been minimised.
- The organic content should have been eliminated from BDs.

The potential contractor was required to define the characteristics of the treatment plant suitable to perform the tests on simulated BDs. Performing the tests on a small-scale pilot plant was allowed, provided that the contractor could demonstrate the validity of test results for the corresponding full-scale plant.

There was a design requirement to include a detailed description of the pre-treatment and treatment process, accompanied by relevant process diagrams, test procedures, and a conceptual proposal for additional treatment or conditioning that might have been necessary (say, for example, if the residuals and/or secondary waste were not compliant with the JRC´s waste acceptance criteria (WAC)).

The potential contractors were free to select and propose the treatment technology, and to prepare the treatment plant to perform a test campaign with the simulated BDs, in order to satisfy the following requirements:

- A global minimum VRF of 2 with respect to the volume of residual waste (including secondary waste and other waste that could not be treated).
- Organic waste shall be eliminated or minimised. The residual weight of organic waste needed to be less than 10% of the initial weight recorded in the BD.
- The selected technology was expected to yield residual waste and secondary waste preferably freely releasable and which complies with JRC WAC.
- For instances when the characteristics of the residual waste / secondary waste / other waste that cannot be treated do not comply with any JRC WAC, a suitable post treatment or conditioning/immobilisation process was expected to be preliminarily defined to be further adopted with the scope to produce the waste forms fully complying with JRC WAC. The global VRF target (which refers to the volume obtained after a further treatment or immobilisation step has been performed) should not have been lower than 2.

The VRF was calculated using the following formula:

$$VRF = \frac{n \cdot NV_{ini}}{m \cdot NV_{fin}}$$

And the nomenclature was defined as such:

- n is the number of simulated BDs used in the test,
- NV_{ini} is the nominal volume of the simulated BDs (217 litres),
- m is the number of the final containers (even if partially full) obtained at the end of the test,
- NV_{fin} is the nominal volume of the final containers.

The organic residue was computed as a weight ratio between the organic content (bitumen plus technological waste inside the compacted small drums) in the final product versus the initial BD.

The potential contractors were requested to prepare a technical proposal for the pilot test execution including at least the following information:

- The identification of the plant to be used to perform simulated BDs pre-treatment, which included the facility´s location and the name of the owner/operator of the facility.
- Preliminary definition of the pre-treatment process that would be further refined during the engineering phase of the pilot test. This preliminary definition was expected to include at least:
    - equipment,
    - tools and machinery to be used,
    - the technology for treating each material,
    - identification of materials excluded from treatment,
    - a description of materials sorting.
- Throughput of the pilot test facility (if the pre-treatment and treatment stage have different processing capabilities both throughputs will be declared), including treatment time and corresponding number of drums to be treated.
- In the event that a mock-up or laboratory scale plant was selected to be used for the test, a preliminary demonstration of applicability of the process to the full-scale plant needed for the service contract was expected to be presented. The demonstration was expected to include:
    - Evidence of how the limited throughput of the proposed small-scale facility would be extended during the service contract to cope with the requirements and duration of that contract.
    - Sufficient spare capacity to ensure that the requirements of the service contract were met.
    - To demonstrate pre-treatment viability, proof that the non-radioactive form of the mock-ups did not prevent the process from being readily adapted for nuclear purposes (not applicable for already licensed nuclear facilities).
- Preliminary planning of contract execution in the form of a Gantt chart.

3.3. Specimens used for the pilot tests

The mock-ups to be used in the tests were provided by the JRC. The mock-ups did not contain any radioactive material except for material bearing natural radioactivity.

The potential contractors had to define the quantity of simulated BDs required for the tests taking into account the following constraints:

- The quantity of mock-ups were expected to lie in the range of 5 to 15.
- Treatment capacity depended on the size of test plant (full scale or pilot scale).
- Following an assessment of repeated treatment test performance, a maximum tolerance equal to ±20% was deemed acceptable.
    - The above test compared the results of at least two successive test runs, i.e. processing parameters, quantity and physical-chemical characteristics of residual waste and secondary waste.
- Each test run was expected to last for enough time, at steady operating conditions and depending on the proposed treatment technology, in order to be representative of the process in continuous operation.

A limited number of simplified mock-ups were available to execute preliminary tests that were not subject to monitoring by the JRC and did not contribute to the assessment of final pilot test performance.

The specimens of simulated BDs consisted of:

- a standard UN 220 L metallic drum,
- a bitumen matrix,
- conditioned solid waste in form of technological waste contained in compacted small drums.

Figure 1 shows the layout of a simulated bitumen drum, whereas **Table 1** reports its main characteristics.

The waste consisted of four 60 L compacted drums containing mixed technological soft solid material, such as polyethylene, rubber, latex, polyurethane, PVC, paper and cardboard.

An inner 115 L drum without a lid was used to simulate the centring metal sheet used in the preparation of most bitumen drums.

Stones were added to the upper part of the drums because stones were used in the real BDs to avoid buoyancy of the waste during bitumen filling. The proportions of the stones were between 20 to 40 mm in diameter for an average weight of 12 kg per drum.

Sand was added to simulate the presence of the solid component of sludge mixed in the conditioning matrix. The sand was present at the bottom of the 220 L drum in the proportion of 4 kg per drum.

The bitumen used as conditioning material to make the matrix was a commercial type of oxidised bitumen (its characteristics are given in **Table 2)**.

The simplified version of the simulated drum, used for preliminary tests, was similar to the nominal version except for the following differences:

- absence of stones,
- absence of sand,
- absence of 115 L drum as an internal layer,
- increased number of compacted small drums from 4 to 5 per each drum.

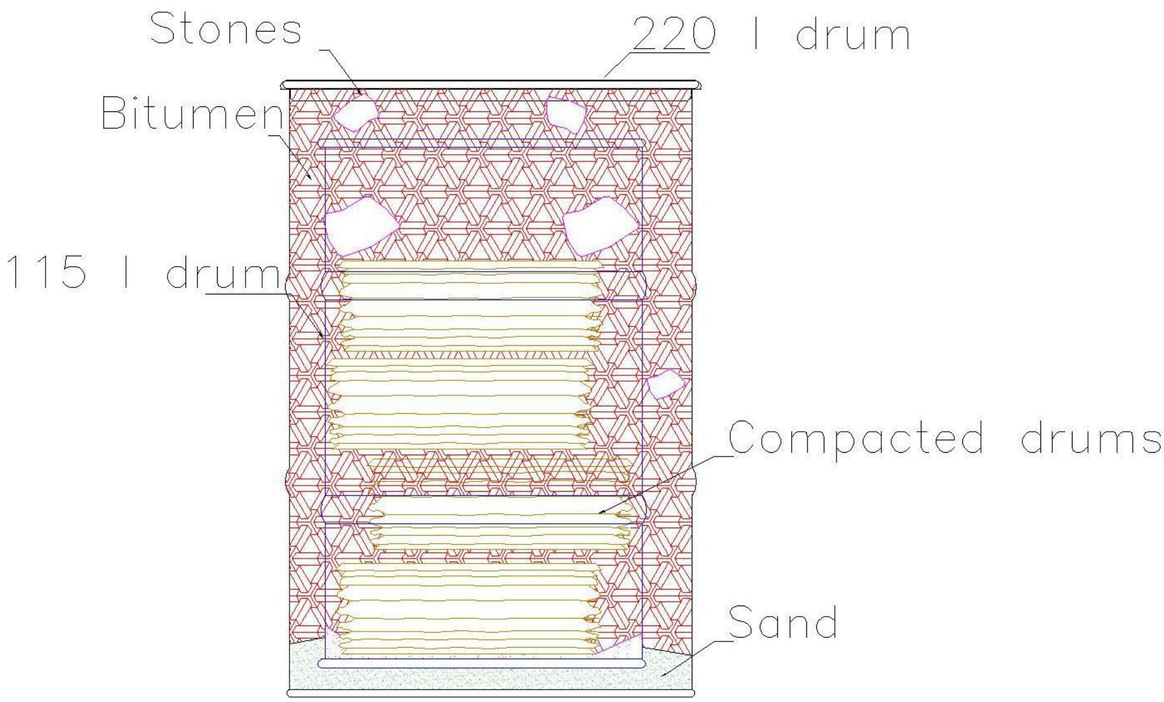


Figure 1: Internal structure of a simulated bitumen drum

Table 1: Characteristics of the 220 L drum

Characteristic	Value
Height (mm)	880±10
Diameter – lid (mm)	605±20
Diameter – internal (mm)	571±20
Nominal volume (L)	217±2
Weight (kg)	22±2
Material (AISI)	1010
Lid thickness (mm)	1±0,2
Wall thickness (mm)	1±0,2
Bottom thickness (mm)	1±0,2

Table 2: Characteristics of bitumen

Characteristic	Test method	Value
Penetration at 25C° (0,1 mm)	EN 1426	10÷20
Softening point ring and ball (C°)	EN 1427	100÷110
Fraass breaking point	EN 12593	≤-3
Flash point (C°)	EN ISO 2592	≥250
Solubility (%)	EN 12592	≥99

3.4. Structure and content of the case studies

Chapters 4 to 9 present the results of each of the six pilot tests executed at the six plants. Each chapter has the same structure across the three sections:

- The first section gives a more detailed description of the plant/process than those summarised in section 3.1.
- The second section describes the main outcomes of the tests. As explained above, the results are primarily presented in a qualitative form without detailed quantitative parameters in order not to breach the confidentiality clause included in the contracts.
- The third section briefly summarises the pros and cons of each technology.

Finally, chapter 10 draws on the main conclusions and lessons learned from the entire exercise.

4. CASE STUDY No.1

4.1. Description of the technology and process

The plant proposed from the first potential contractor was an already operational complex with a vast experience both in incineration of RAW and in treatment of radioactive metal waste. Nevertheless, the plant was not ready to directly accept mixed waste with burnable technological and metal mixed into a bitumen conditioning matrix.

In order to be processed, the BDs needed to be pre-treated. This consisted of:

- Freezing the BDs at -10 ºC in an industrial deep freeze machine.
- Mechanical fracturing.
- Segregation of different components (technological waste, metal, bitumen and other non-burnable waste) in HDPE drums (non-metal) and 200 L steel drums (metal).
- (Eventually) washing of metal with solvent for removing traces of bitumen.
- Retrieval of bitumen and packaging in HDPE drums.

The sterile (non-metal and non-burnable material, such as stones, sand, glass etc.) waste was returned as non-treatable waste. Then the incineration took place at the plant's incineration unit, which had the technical capacity of a large throughput, i.e. several thousand tonnes per year. The process was based on a static fuel furnace working at around 1000 ºC with two main chambers:

- The primary one was dedicated to solid combustible waste and aqueous liquids. This was used for the combustible technological waste coming from the segregation step described above.
- The second one was dedicated to organic liquid waste and was used to incinerate the bitumen.

The plant was provided with a very efficient off-gas treatment system with quench tower, bag filters, Denox and Dedlox system, and HEPA filters in full respect of environmental regulations. The plant was capable of accepting many types of operational solid waste (e.g. dry spent exchange resins, clothes, soft organics, plastic, woods – preferably compacted) in HDPE or 220 L steel drums and non-solidified liquid waste (e.g. bitumen, chemical solutions, evaporation concentrates, oil, solvents, TBP) in 200 L drums or ISO 20' tanks. The secondary wastes that arose from the incineration were mainly ashes and clinker that were normally conditioned in a hydraulic matrix in 400 L steel drums.

The average performance of the incineration plant in volume reduction was approximately 93% for standard waste treatment. Furthermore, the separated metal items were treated in the melting unit, equipped with a 4-tonnes capacity induction furnace, also with a throughput of several thousand tonnes per year. It melted radioactive material in stainless steel, carbon steel and, to a lesser extent, non-ferrous metals. Depending on the quality of the incoming steel, it allowed recycling part of the waste. The secondary waste from the metal melting unit were cast ingots conditioned in 200 L steel drums, dust and refractories. The average performance of the metal melting plant in volume reduction was approximately 84% for standard waste treatment. The entire process is displayed in **Figure 2**.

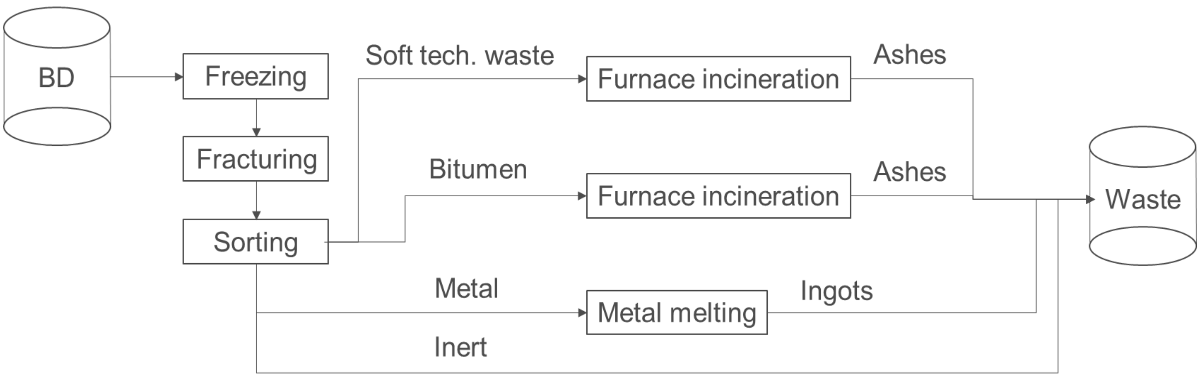
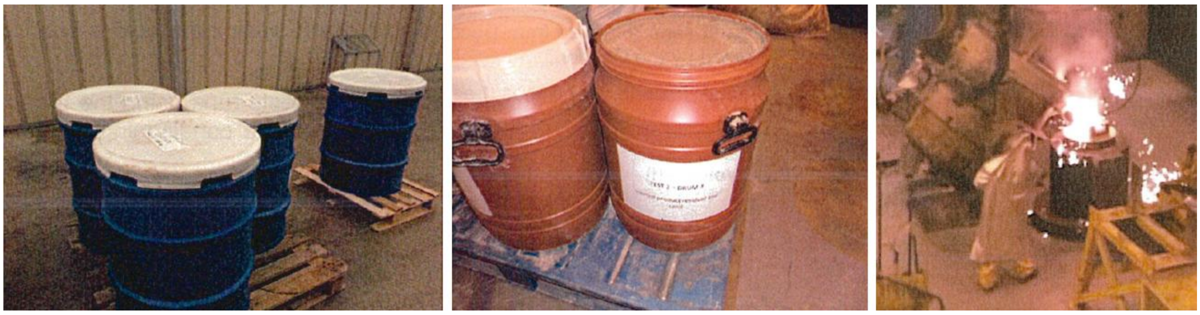


Figure 2: Process of case study #1

4.2. Results

Six (6) simulated BDs were used in this pilot test: two batches of three drums to demonstrate reproducibility. The deconditioning pre-treatment campaign took approximately two (2) weeks per batch and proceeded without any major problems. Then the incineration and melting tests were successfully performed in the plant.

Figure 3 shows some pictures taken during the test: sorted combustible waste packaged in PE drums ready for incineration (a), conditioned final waste (b) and metal melting (c).



(a) (b) (c)

Figure 3: Pictures from case study #1

The main results can be summarised as:

- The two batches gave consistent results within a few percents confirming the reproducibility of the process.
- The final residues were only a few percents of the initial organic content (target <10%) and the total organic content in the final residues was well below 1%, which met the target values.
- The VRF met and exceeded the target value of 2.

The process proved to be apt for the reconditioning of the BDs.

4.3. Summary of pros and cons

The proposed technology was fully mature. Both processes for organic incineration and metal melting are widely applied in RAW management. The proposed methods present a particular advantage by providing a large throughput (thousands of tons per year).

The technical performance was excellent and exceeded the target values, both in terms of VRF and final organic residues.

The only weakness of the method was the required pre-treatment for which there was not an existing plant and the operator had to develop an ad-hoc solution. The proposed pre-treatment was relatively time consuming and was mostly performed by manual operations with the aid of mechanical tools in a confined environment. This caused workers to be exposed to the waste for relatively long periods of time, which limited the operation to waste with low dose rates. For the JRC case, this is acceptable, since the drums were expected to contain VLLW, but for other costumers having to treat waste with higher dose rates, the pre-treatment process would need to be implemented differently in a shielded environment.

5. CASE STUDY No.2

5.1. Description of the technology and process

The proposed process was an already operational plant used on a site engaged in a NPP decommissioning programme in an EU Member State. The typical throughput of the plant in the past was of the order of 100 tonnes per year.

The incineration facility had two chambers: the main incineration furnace and the afterburner chamber. Combustible solid RAW was packed into plastic bags in the sorting box. The bags with waste were put into the incineration RAW facility by means of feeding equipment.

The incineration facility was divided into the following technological process sub-systems:

- solid waste supply,
- RAW incineration,
- flue gas cleaning,
- fine filtration,
- vacuum maintaining,
- ash discharge,
- liquid waste supply,
- spent resin feeding.

Solid and liquid RAW were incinerated in the main incineration furnace at a temperature of 750÷950°C. Ash and flue ash produced in the process of incineration settled at the bottom of the main incineration furnace and afterburner chamber. After the incineration of RAW within the cycle, the ashes were discharged after recooling into 200 L drums. Flue gases leaving the furnace were post incinerated in the afterburner chamber at a temperature of 1000°C, went through a solid particles filter and were subsequently post-cleaned by two-stage scrubbing utilising high-performance scrubbers and cellulose absolute filters.

Combustible solid RAW was transported by a conveyor in 200 L drums. Then packed in 30 L bags containing 3-8 kg of combustible waste and fed into the furnace. Based on heating values and contents of bags with solid RAW, it was suitable to regulate the feed rate into the furnace at intervals of 5-10 minutes.

The upper part of the afterburner chamber was used to burn additional fume flue gases which exited the main furnace. The lower part of the afterburner chamber was used to cool the fume flue gases. Cooled fume flue gases left the bottom part of the afterburner chamber through a nozzle. Air necessary for natural gas combustion during post-incineration was sucked through a filter.

Flue gases which exited the afterburner chamber were cooled down to the required temperature, then passed through the flue gas cooler into the regeneration sleeve filter. The solid particles were captured along the entire surface of the sleeves in the form of a filter cake. Filtration sleeves were regularly regenerated and ashes were emptied into the after-cooling chamber under the sleeve filter and then to the ash conveyor.

Flue gases then passed through a further fine filtration step.

A vacuum needed to operate the incineration facility was created by means of a main blower.

Ash generated in the furnace and afterburner chamber was discharged into the ash discharge boxes and the ash from the furnace was emptied after incineration of about 1 tonne of solid RAW, as well as the ash from the afterburner chamber. Ash from the furnace remained inside the area to cool the ash discharge box until the next load was emptied.

The process described above required a precise dosage of organic content introduced into the furnace, in order to meet the input technical specifications of the plant and to ensure optimal mixing with the air input flow. Furthermore, the BDs were unable to enter without being reduced in size. Due to the composition of JRC BDs, the optimal size of each batch was around 4 kg of waste. Therefore, they needed to be pre-treated to meet the plant input specifications.

The pre-treatment consisted of: opening and sorting of non-burnable components (sand, stones and metal fragments, to be compacted), ultrasonic-enhanced dissolution of bitumen with organic solvent into a dissolution tank, separation, cleaning and compaction of metal components, fragmentation, post-processing and packaging of burnable organic material suitable for the incineration plant.

Past experience with the incineration process gave an average weight reduction factor higher than 20.

Waste from incineration were ashes filled in 200 L drums. These were compacted and grouted into 440 L drums, together with metal and other non-burnable waste.

The entire process is described in **Figure 4.**

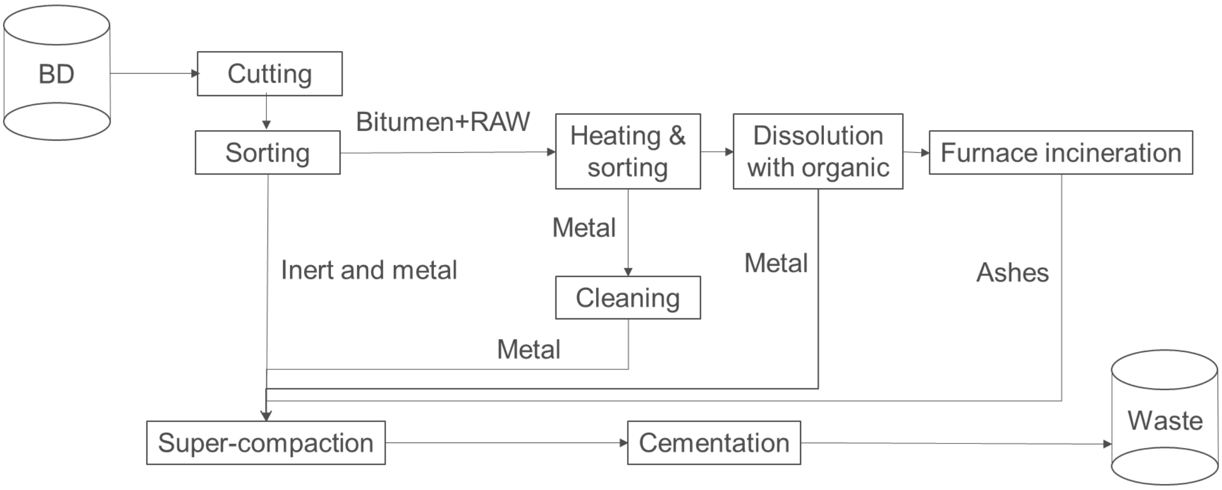


Figure 4: Process of case study #2

5.2. Results

The pre-treatment proved to be the most sensitive part of the process. The first test of direct dissolution of the entire BDs resulted in only a partial removal of bitumen. Then the test was continued with a mechanical separation and fragmentation of the bitumen, not initially planned in the test procedure. The liquid waste (solvent and dissolved bitumen) was then fixated in a sorbent material. The entire pre-treatment took approximately two weeks. A second batch, profiting from the previous experience, was pre-processed in a week. Then a third batch followed.

Figure 5 shows some pictures taken during the pre-treatment: the BDs after dissolution (a) and the sorted inner drums (b).

(a) (b)

Figure 5: Pictures from case study #2

After the pre-treatment, the operator executed the incineration process, which proceeded as expected with good performance, summarised as:

- The test confirmed the expected reduction factor of 20, when considering the burnable organic content only
- The overall VRF, considering also the non-burnable component, met and exceeded the target value of 2
- The final residues were only a few percents of the initial organic content, meeting the target value (<10%)
- The three batches gave consistent results confirming the reproducibility of the process

The process proved to be apt for the incineration of organic waste, even though the pre-treatment process would need to be improved in order to be fully usable for reconditioning the BDs.

5.3. Summary of pros and cons

The proposed technology was fully mature, especially considering the use for waste apt for direct incineration.

The technical performance was excellent and significantly exceeded the target values both in terms of VRF and final residues.

The throughput was limited by the small size of the plant and the required parameters of the feed rate.

The pre-treatment by dissolution with solvents proved to be quite cumbersome for processing the JRC BDs.

6. CASE STUDY No.3

6.1. Description of the technology and process

The plant was an existing and operational large-throughput commercial plant located in an EU member state, licensed to treat dry LLW, activated charcoal, ion-exchange resins, and liquid waste in the forms of oils, sludges and solvents.

The incinerator accepted a feed up to 35 kg of waste every ten (10) minutes. Direct feed of drums was not allowed, so it required a pre-treatment process.

The envisaged pre-treatment process for the JRC BDs consisted of heating the BDs in a specially designed heating cabinet to approximately 200 °C, to liquify the bitumen and to separate it from the compacted small drums. The separated bitumen was packed into polyethylene bags. This was followed by dry ice blasting to remove bitumen residuals from metal surfaces, then further heat treatment and final shredding of the compacted small drums.

The compacted drums were shredded in a waste shredder which created flakes. The metal fraction of the waste from the compacted drums was retained for incineration (separation would have been possible, but retention of bitumen stuck to the metal parts would have increased the organic content in the final waste).

After shredding, the incineration of bitumen and shredded compacted drums was performed using the existing Incineration facility. Both the bitumen and the shredded waste had been packed into bags prior to this step. The waste was fed into the incinerator using the existing conveyor system. The incineration plant had a capacity of nearly 2000 kg per day.

The material originating from the pilot tests was fed into the incinerator using the existing conveyor system, in accordance with the operating manual of the plant (maximum 30 kg in each conveyor bin).

After incineration the ash was collected in drums, weight and volume could then be defined and measured.

This plant also, like the one described in case study #1, had the possibility to offer metal melting treatment for the metal parts. This made it possible to partially recover the secondary waste, which might have also been clearable and recyclable.

The entire process is described in **Figure 6.**

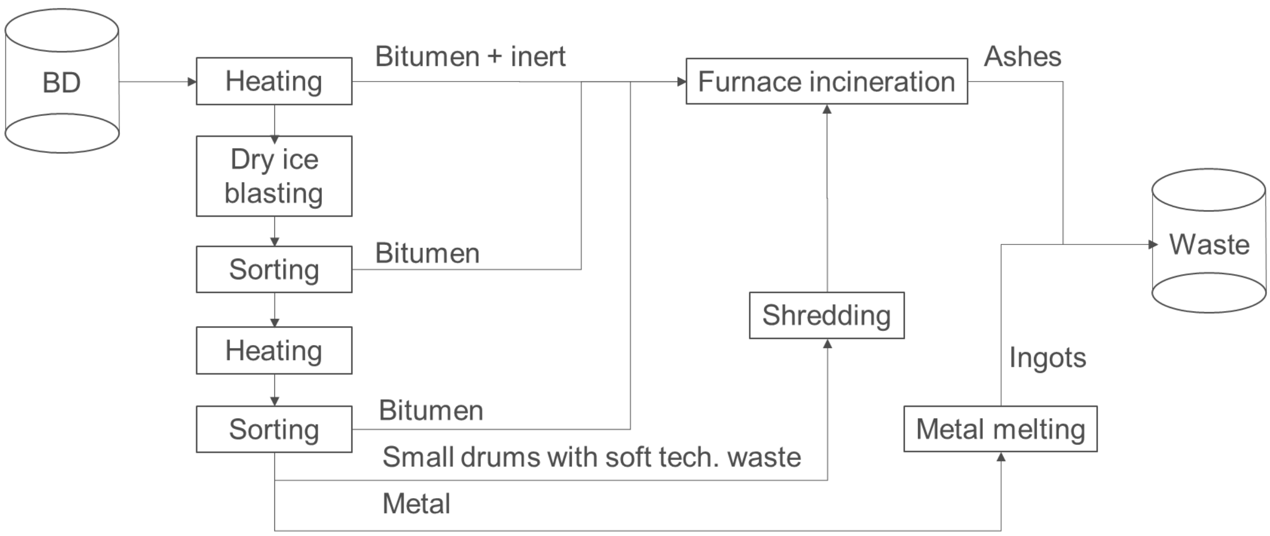


Figure 6: Process of case study #3

6.2. Results

Five BDs were used for the pilot test for a total of nearly 2000 kg of waste.

The pre-treatment by heating and successive dry ice blasting was successful, allowing for the recovery of more than 99% of the initial bitumen. The further heat treatment did not bring any further benefits, so the pilot test acted as a means of learning from, assessing and improving the designed pre-treatment process.

Figure 7 shows some pictures taken during the test: the heating cabinet (a), collection of melted bitumen (b), sorting (c).

(a) (b) (c)

Figure 7: Pictures from case study #3

After incineration, the analysis of secondary waste revealed that:

- VRF met the target value >2
- Organic residual was only a few percent, which met the target value of <10%

The test performed on a few BDs led to partial filling of secondary waste drums. It was possible to estimate the asymptotic VRF and organic residues of large batches that would generate a further improvement of the final VRF and organic residue values.

6.3. Summary of pros and cons

The proposed technology can be considered mature because both processes for organic incineration and metal melting are widely applied in RAW management. The proposed methods presented a clear advantage of providing an extremely large throughput.

The technical performance was excellent and exceeded the target values, both in terms of VRF and final residues.

The drawback is again the need of an ad-hoc pre-treatment process, which in this case proved to be relatively simple and effective.

7. CASE STUDY No.4

7.1. Description of the technology and process

The plant was an operational commercial incinerator used for generic industrial hazardous waste, including petrochemicals, oils, sludge, pesticides, resins, laboratory chemicals, pharmaceuticals and, under specific conditions, RAW. The throughput of the plant was several tens of thousands of tonnes per year.

It was possible to directly feed the 200 L drums, or to shred them first, before being processed. Pre-treatment was only required for those drums that did not meet the acceptance criteria (damaged, overweight etc.). The bituminised drums were frozen at -20°C for several days in order to ensure the bitumen was brittle enough to fracture under the action of the shredder. The resultant material was then re-packaged into drums to be fed into the incinerator.

The waste was loaded into the incinerator, which was always kept under-pressure to avoid release of dangerous substances to the environment. The combustion took place at temperatures above 1100°C for approximately two hours for a complete disintegration of organic materials. The furnace was a rotary kiln, a large revolving refractory-lined stainless-steel drum with a shallow inclination, allowing the waste to move slowly from the feed to the discharge end. Then the effluent was subject to extensive gas cleaning in order to comply with environmental regulations. The gas was then sent to an after-burner chamber to ensure that the organics were completely destroyed, after which the gaseous stream was subsequently passed through a further cleaning process.

The waste was a solid, inorganic and inert ash in vitrified form and included all non-combustible components. The JRC BDs included the carcasses of the external 200 L drum and the internal compacted small drums. The ashes also included secondary waste, such as process filter cakes, both received from gas cleaning and from liquid effluents treatment.

If the final ashes complied with the local environmental regulations, they were released to landfill and no waste was returned to the waste owner/producer.

Typical results from operations resulted in a volume reduction of 85%.

The entire process is described in **Figure 8.**

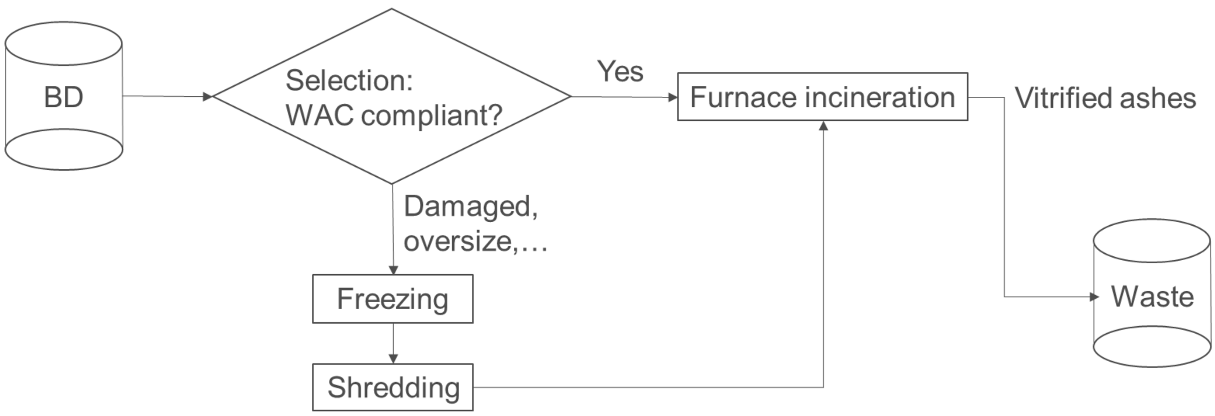


Figure 8: Process of case study #4

7.2. Results

Four drums were directly processed, whereas the other eleven were pre-treated.

For the purpose of the test, the plant rented a commercial freezer unit and four commercial shredders to perform the pre-treatment. The freezing process required seven days, after which the shredding phase proceeded very fast, less than 20 minutes per drum. A test made by shredding a non-frozen drum was unsuccessful, confirming the need of the preliminary freezing step.

The secondary waste complied with environmental limits, so it was disposed of locally.

Figure 9 shows an example of shredded material after pre-treatment.

Figure 9: Shredded material after pre-treatment

The overall test performance is summarised below:

- The test fully confirmed the reproducibility of the process.
- VRF met and largely exceeded the target value of >2.
- The final organic residue met and largely exceeded the target value of <10%.

7.3. Summary of pros and cons

The case study was interesting because it was performed in a general industrial waste treatment plant and not in a dedicated incinerator for RAW. This allowed the simulated BDs to be easily treated, but when treating drums containing RAW, the proposed process would need some adaptation.

For instance, shredding was carried out using a rented industrial shredder. For the case of treatment of a large number of BDs containing real RAW, a different dedicated shredder should have been designed and procured, in particular with the requirement of a closed environment to contain dust and fragments generated during the shredding.

The high temperatures required for the hazardous chemicals guaranteed that bitumen and the ordinary organics contained in the JRC BDs could be adequately destroyed.

While the fact that the final waste could be eventually disposed of locally might be very attractive for the potential customer; it poses regulatory issues when dealing with RAW. In fact, the Euratom Directive 2011/70 only allows disposal of RAW in a country different from the producer’s after an inter-governmental agreement between the two states.

8. CASE STUDY No.5

8.1. Description of the technology and process

The plant proposed by the potential contractor was an operating plant for RAW incineration located in a non-EU country.

From previous experience on pure organic waste, typical VRFs can reach a range of up to 30÷100.

Since the plant had no previous experience in the treatment of bituminised drums, they decided to test several possible pre-treatment routes. All the pre-treatment tests used already existing equipment available at the plant.

The first and simplest method was a direct feed of an entire drum into the oven after only boring radial holes from the drum walls.

The next method involved cutting drums into two halves on the vertical plane using a band saw. A drum was cut at room temperature, whereas a second one was preliminarily frozen for several days at -20 °C.

Finally, a further pre-treatment method included shredding quarters of drums after double cutting. Also, in this case the test involved drums with or without previous freezing.

The purpose of boring, cutting and shredding was to optimise the surface area of the bitumen and technological waste to the heat inside the oven in the following incineration process. The pre-treated BDs were finally fed into the burning process unit. This consisted of an oven operating at approximately 1000 °C, followed by a thermal oxidizing unit, a quench unit based on a spray tower, a re-heat unit, HEPA filters and stack.

The resulting residues (ashes) and the non-burnable material were placed into 220 L drums and then compacted. The non-burnable component, when separated, was potentially releasable if below regulatory limits. However, since the pilot tests were executed on simulated non-radioactive material, it was not possible to assess the releasability and the consequent potential increase of the final VRF. According to the local rules, secondary waste generated by the process included HEPA filters which were a liability of the plant (to be disposed of locally and not to be returned to the customer).

The entire process is described in **Figure 10.**

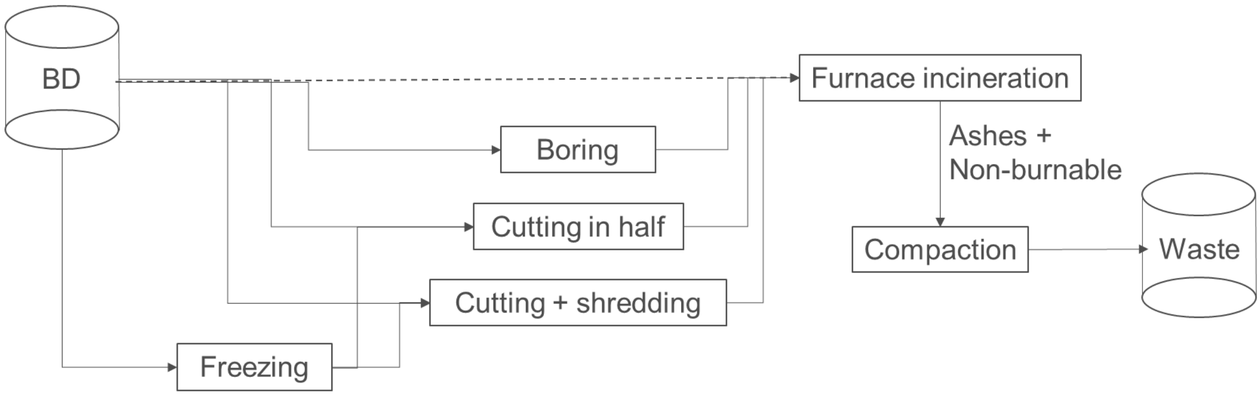


Figure 10: Process of case study #5

8.2. Results

The plant used twelve simulated BDs, two for each of the tested pre-treatment paths.

Through comparing the different pre-treatment processes, it was found that cutting plus shredding was advantageous when compared to the separation of components, allowing for the potential free release of the non-burnable inert material. The option of freezing/cutting/shredding proved to be the best method to optimise the efficiency of incineration. Nevertheless, since the simplest pre-treatment method by hole boring proved to be sufficient to reach the performance target, this was the preferred choice for the operator and the reported results refer to this option, even though they did not perform quite as well.

Figure 11 shows some pictures taken during the pre-treatment tests: boring (a), cutting in halves (b) and (c), shredding (d) and (e).

(a) (b) (c) (d) (e)

Figure 11: Pictures from case study #5

In this case the results of the process can be summarised as:

- VRF met the target value of >2
- The organic residual meets the target value of <10%

The potential service provider explicitly stated the possibility to freely release the separated inert material (sand and stones) and eventually the metal, which led to a considerable increase of the final VRF.

8.3. Summary of pros and cons

The technology proved to be fully mature and totally apt to process the BDs.

Concerning the pre-treatment, a flexible approach was taken to defining the preferred option depending on the final goals and conditions: minimised effort and consequently processing costs and the maximisation of the safety of operations. Whereas the most sophisticated process (freezing, cutting and shredding) was more expensive, needed to be operated in a closed environment in order not to disperse dust and fragments. But, conversely, it should be noted that the possibility of releasing non-burnable components can result in drastic performance improvements when undertaken.

9. CASE STUDY No.6

9.1. Description of the technology and process

The last case study refers to a proposal for incineration not based on furnace incineration, but on the use of a plasma torch. At the time of the pilot test, the plant did not exist and the potential contractor had plans to build it in an EU country.

Despite the successful pilot test, the potential contractor did not follow-up on the plans and the plant was never built. So, today there are not any commercial operators in Europe offering services for plasma torch incineration. Nevertheless, it was decided to report on the case study here because the tests performed well and the technology could potentially be of interest in future developments. Although, it would be remiss not to acknowledge that there are currently two plasma melting operating plants in Europe. At the moment the two plants are limited to domestic use by licensing and contractual issues, so they are not available to external services on the open market. A good description of the plant operated by SERAW at Kozloduy (Bulgaria) NPP is available in reference [2].

The pilot test program used an existing arc plasma melting facility located in a non-EU country to demonstrate the treatment of the simulated BDs. This facility had been successfully used for numerous pilot scale test programs including the batch treatment of whole drums containing inorganic waste and continuous gasification/melting. The primary approach was to perform batch treatment of several BDs. The arc plasma melting process eliminated the organic contents from the BDs and melted the residual inorganic waste. The melted inorganic waste was poured into a containment vessel and allowed to cool and to form an inert glassy slag solid of minimum size. Multiple test campaigns were performed to demonstrate process repeatability.

In addition to the above, as an alternative to the batch treatment of whole BDs at the plasma melting facility, a pre-treatment process was performed. Shredding tests for waste fragmentation and homogenization before their processing by the plasma melting facility were carried out at another plant. The shredded material was collected in drums and transferred to the plasma melting facility for further treatment. The operator tested several pre-treatment options: direct entire drum shredding, mixing with wood and shredding, freezing with dry ice and shredding.

The incineration took place in a high temperature plasma chamber (refractory-lined with 1500ºC max temperature). The oxygen was monitored in the refractory-lined exit duct for complete combustion detection. The combustion air was injected directly into the chamber to attain the required degree of combustion. Since the test was performed in a small-scale demonstrator, the internal volume was limited to 1.2 m^3. The chamber had a tilt design for melt discharge and collection.

After plasma treatment, the flue gasses entered the off-gas system to remove the chemical substances to an acceptable level obtaining flue gasses practically free of dust.

The hot slag was poured into a containment vessel that allowed the cooling to form an inert glassy slag solid of minimum size. At the end of the process, a robust conditioned product was obtained, free from liquids and organic material and meeting all technical specifications and waste acceptance criteria for long-term storage. The secondary waste included ashes generated by the cyclone and the off-gas system´s bag house filter.

The entire process is shown in **Figure 12.**

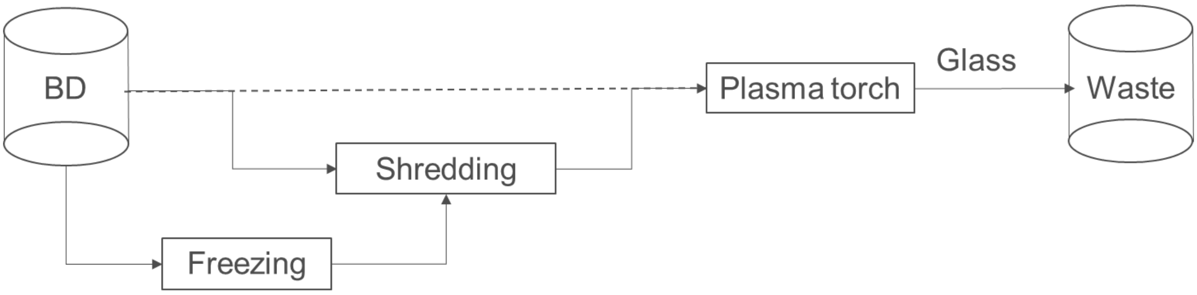


Figure 12: Process of case study #6

9.2. Results

Twelve simulated drums were used to test the different pre-treatment options. Among the different pre-treatment routes, the one that involved freezing before shredding proved to be the most effective. This option was selected for the treatment testing campaigns.

After pre-treatment, six BDs were fed into the treatment facility at a rate of a drum every two hours. The entire treatment testing campaigns lasted four days.

Figure 13 shows some pictures taken during the tests: waste after pre-treatment by freezing and shredding (a), pouring the sludge after plasma melting (b) and the final product (c).

(a) (b) (c)

Figure 13: Pictures taken during case study #6 tests

The results can be summarised as:

- The VRF largely exceeded the target value >2.
- The final waste was almost entirely free from any organic material, largely exceeding the target value of <10%.

9.3. Summary of pros and cons

Due to the higher operating temperatures, the plasma melting technology performed better than classical furnace incineration: which meant almost all organic content was destroyed and, by melting the metal components, a greater VRF was achieved.

Furthermore, considering the current state of the market at the time of writing, specifically a lack of a commercial plant based on the available technology, it can be inferred that the technology elucidated presents a potential alternative in the future based on its reported ability to satisfy customers' needs.

10. SUMMARY OF LESSONS LEARNED

The pilot tests covered the feasibility of incineration for volume reduction and organic destruction in drums containing VLLW/LLW conditioned in a bitumen matrix.

The tests included several methods and technologies: incineration in furnaces (either specifically dedicated to RAW or for general industrial hazardous waste) and plasma torches.

In most of the cases, the BDs used in the exercise did not meet the conditions for direct feed into the treatment process, which required them to be pre-treated. In most of the plants, the pre-treatment was not part of the routine operation, so the operators had to envisage, design, set-up and test the pre-treatment process, which generally proved to be the most challenging step of the exercise.

Concerning the tested pre-treatment methods, generally those based on thermal processes (either by freezing or by heating) proved to be easier to implement and more effective than those based on chemical (dissolution with solvents) or mechanical (boring, cutting, shredding) processes.

Concerning organic destruction, all the tested technologies proved to be largely suitable for incineration of BDs. The organic destruction rate exceeded 90% in all cases, largely meeting the expected target value of the final residues (<10%). Generally, we observed an increase of destruction rate when increasing the process temperature, as can be reasonably expected.

Such a strong performance also helped to meet the VRF target (VRF > 2) in all the tests. Indeed, the quantitative results showed that the final VRF was very similar for all technologies based on furnace incineration with values spanning a relatively narrow range.

This can be explained by the fact that the overall VRF was only loosely dependant on the organic destruction efficiency, and was mostly dominated by the content of non-burnable material (metal and inert materials) inside the BDs. Since the initial content of non-burnable components was the same in the simulated BDs, the VRFs recorded were similar for all the technologies.

The plasma melting technology was reported to be very effective and presents a potential alternative opposed to furnace incineration, while still satisfying requirements in terms of both VRF and organic material. However, the only impediment to utilising this technology, at the time of writing, is that there is a lack of such plants in commercial operation.

Concerning the post-treatment operations, some plants offer the possibility to treat the metal components by melting. This treatment method provides the opportunity to clean the metal below the clearance levels and to recycle the decontaminated metal material. The VRF was found to improve when such an approach was taken. Since the pilot test was carried out on simulated non-radioactive BDs, the metal melting process was not executed during the pilot tests, since it would not have given any significant indication about the amount of recyclable material and secondary waste.

Table 3 below summarises the characteristics of the methodologies of the six case studies and reports the "typical" performance values. The results of the individual tests cannot be disclosed, due to a confidentiality clause; nonetheless, since all the tests produced similar and consistent results, reporting the range of results in an aggregated form should not breach any individual confidentiality constraint.

Table 3: Summary of tested incineration technologies and processes.

<table>
<tr><th rowspan="2">Case study #</th><th rowspan="2">Treatment process</th><th rowspan="2">Pre-treatment</th><th rowspan="2">Post-treatment</th><th rowspan="2">Plant throughput (tons/year)</th><th colspan="2">Typical performances</th></tr>
<tr><th>VRF</th><th>Organic residue</th></tr>
<tr><td>**1**</td><td>RAW furnace</td><td>Freezing + fragmentation
Segregation</td><td>Metal Melting (optional)</td><td>~10^3</td><td rowspan="5">2.5 to 4.8</td><td rowspan="5">0.2% to 3.0%</td></tr>
<tr><td>**2**</td><td>RAW furnace</td><td>Dissolution with solvents</td><td>Compaction</td><td>~10^2</td></tr>
<tr><td>**3**</td><td>RAW furnace</td><td>Melting by heating
+ Shredding</td><td>Metal Melting (optional)</td><td>~10^3</td></tr>
<tr><td>**4**</td><td>Industrial furnace</td><td>None or
Freezing + Shredding</td><td>Possible disposal</td><td>~10^4</td></tr>
<tr><td>**5**</td><td>RAW furnace</td><td>Boring or
Cutting or Cut + Shredding
or Freezing + Cut./Shred.</td><td>Compaction</td><td>~10^3</td></tr>
<tr><td>**6**</td><td>Plasma melting</td><td>None or Shredding or
Freezing + Shredding</td><td>None</td><td>N/A</td><td>5 to 9</td><td>~ 0</td></tr>
</table>

REFERENCES

[1] Technical specifications for the execution of a pilot test, JRC internal document, NE.45.2604.A.005, (2011).

[2] Treatment of low and intermediate level radioactive waste using Plasma Melting Process, and Performance Analysis, KP-SERAW-002, (2022), available at link: https://joint-research-centre.ec.europa.eu/scientific-activities-z/eu-nuclear-decommissioning-knowledge-management/decommissioning-knowledge-products_en