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Strategic Study of Thermal Treatment of European Radioactive Wastes

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Abstract. Under Work Package 2 (WP2) of THERAMIN, strategic reviews of thermal treatment technologies and European radioactive waste streams for which thermal treatment could bring benefits have been undertaken. This paper presents the outcomes of an international review of inventory information concerning European wastes potentially suitable for thermal treatment, a review of thermal treatment technologies, and a strategic gap analysis to identify countries where there are significant waste arisings with potential benefits for thermal treatment, but little prospect of these countries developing thermal treatment facilities independently.

1. Introduction

The overall objective of THERAMIN (The **The**rmal treatment for **ra**dioactive waste **min**imisation and hazard reduction) is to identify improved options for safe long-term storage and disposal of intermediate-level wastes (ILW) and low-level wastes (LLW) suitable for thermal processing. The work programme provides a vehicle for coordinated EU-wide research and technology demonstration. It is designed to provide improved understanding and optimisation of the application of thermal treatment in radioactive waste management programmes across Europe, and to move thermal technologies higher up the Technology Readiness Level (TRL) scale.

Under Work Package 2 (WP2) of THERAMIN, strategic reviews of thermal treatment technologies and European radioactive waste streams for which thermal treatment could bring benefits have been undertaken. WP2 is structured in five tasks:

- Task 2.1: development of a European database of radioactive waste groups suitable for thermal treatment.
- Task 2.2: implementing a strategic analysis of the benefits of thermal treatment of the waste groups identified and the risks and barriers that exist to such treatment.
- Task 2.3: summarising the availability and maturity of different thermal treatment technologies.
- Task 2.4: constructing a summary matrix of waste groups and applicable thermal treatment technologies.

- Task 2.5: undertaking a value assessment of the strengths and challenges of selected waste group / thermal treatment combinations.

This paper presents the outcomes of Tasks 2.1 to 2.4. Specifically, this paper focuses on the outputs of an international review of inventory information concerning European wastes potentially suitable for thermal treatment, a review of thermal treatment technologies, and a strategic gap analysis to identify countries where there are significant waste arisings with potential benefits for thermal treatment, but little prospect of these countries developing thermal treatment facilities independently.

2. European wastes Potentially Suitable for Thermal Treatment

A Europe-wide review was undertaken to gather inventory information on radioactive waste streams that could benefit from thermal treatment. Inventory information was gathered by means of a questionnaire from THERAMIN Partner and End User Group countries (Belgium, Finland, France, Germany, Lithuania, Slovakia, Switzerland, UK). In addition, the European Commission (EC) encouraged inclusion of Ukraine, and its inventory was also captured in the waste database. Waste information from the EC project Microbiology In Nuclear waste Disposal (MIND) was also sought, which resulted in the addition of the following countries: the Czech Republic, the Netherlands, Spain, and Sweden.

The waste streams identified were categorised according to waste type and composition into 14 generic waste groups (Table 1) and compiled in an electronic database for presentation and data analysis (Task 2.1, [1]). Each waste group may have specific issues associated with treatment, processing, packaging or transport, although for some groups the issues are common. The categorisation into generic groups was based on commonalities in the waste stream properties and composition. There are common waste types that occur in several countries, such as sludges, ion exchange materials, cement-conditioned wastes, and bitumen-conditioned waste, whilst others were identified as present in fewer countries (e.g. polymer-conditioned waste and non-organic liquid wastes).

The database was used to generate volume information for the generic waste groups across in the countries reviewed. Figure 1 provides a summary of the breakdown of wastes (both existing and future arisings) covered in the database, excluding Ukraine, which would dominate if included because its inventory, which represents the national inventory, is volumetrically much larger than those of other countries. It is noted that the estimated volumes of waste are those that have been deemed potentially suitable for thermal treatment by country contacts filling out the questionnaires. They do not represent the total inventories in the listed countries. In addition, the listed countries in Figure 1 are those that have identified a particular waste as a potential candidate for thermal treatment, noting that thermal treatment may be an alternative to other treatment options rather than an optimized solution. Other countries not listed may hold similar waste but manage it via an already established route.

The database was also used to enable a strategic analysis of the benefits of thermal treatment. The analysis considered the drivers for thermal treatment, and the risks and barriers to applying this treatment. For each country, the analysis described the risks if the wastes are left untreated and potentially without a management route, and identified those wastes for which thermal treatment is unlikely to bring significant benefits. This analysis was supported by a brief description of the national context and programme status in each participating country. The database and strategic analysis are documented in a report (Task 2.2, [2]).

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Table 1. Generic waste groups defined in [2].

Generic waste group	**Description**
Alpha waste (including PCM)	Material contaminated with alpha-emitting radionuclides (e.g., plutonium, uranium, etc.). This waste includes PCM.
Bitumen-conditioned waste	Wastes that have been conditioned in a bitumen matrix. The nature of the original raw waste is varied.
Cement-conditioned solid waste	Wastes that have been conditioned in a cementitious matrix. The nature of the original raw waste is varied.
Filters	Filters are used to remove radionuclides and particulates from contaminated air or other media. Example filters include: HEPA, charcoal filters, and cartridge filters used to remove radionuclides and particulates from active effluent.
Graphite	Waste graphite from decommissioning of reactors that used graphite as part of the reactor design. This could include core graphite or graphite debris from the fuel assemblies.
Hazardous or Chemotoxic waste	Wastes which have chemotoxic properties (e.g., Be, Cd, Hg) or which are hazardous (e.g., asbestos).
Inorganic ion exchange material	Ion exchange materials used for the removal of soluble radionuclides (e.g., caesium) from liquid waste (e.g., irradiated fuel cooling pond water). Example inorganic resins include: zeolites, Ionsiv® and clays.
Metallic waste (pure or high content)	Waste containing pure metal or metal mixed with other materials.
Miscellaneous contaminated solid waste (including PVC)	Other miscellaneous solid waste that is non-metallic, e.g., maintenance wastes, decommissioning wastes, contaminated gravel, concrete, PVC, etc.
Polymer-conditioned waste	Wastes that have been conditioned in a polymer matrix. The nature of the original raw waste is varied.
Organic ion exchange material	Ion exchange materials composed of high-molecular-weight polymers. They are also used for the removal of soluble radionuclides from solution.
Other liquid waste (e.g. Chrompik)	Contaminated aqueous liquids which do not contain organics.
Organic liquids and oils	Contaminated liquid waste which contains organics such as oils or solvents.
Sludge and concentrates	Includes bulk sludge, residuals, and concentrates. Sludges arise in tanks, sumps and ponds, and comprise a mixture of particulate materials and water.

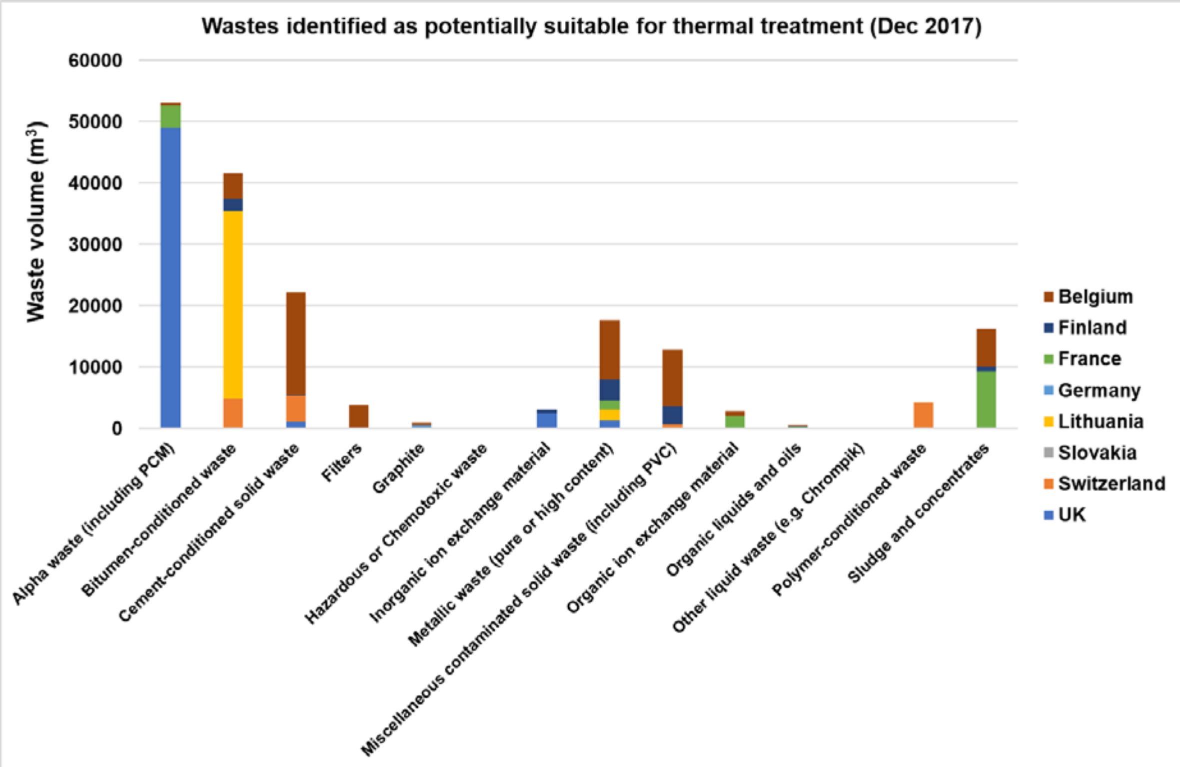

Figure 1. Waste volumes (existing and future arisings) identified for thermal treatment, grouped by generic waste group (excluding Ukrainian wastes). Note that the estimates provided correspond to waste streams identified as potentially suitable for thermal treatment and do not represent national inventories.

3. Thermal Technologies in Europe

Under Task 2.3, a report was produced describing potential thermal technologies available in Europe, and considering, at a high level, the range of wastes and materials that they have demonstrably treated, or are theoretically capable of treating [3]. The objective of Task 2.3 was to summarise the availability and maturity of thermal treatment technologies in Europe by:

- Providing a summary of the current status of each thermal technology with regard to treatment and processing of radioactive wastes.
- Evaluating the availability of thermal technologies to countries with significant waste arisings that could benefit from thermal treatment and processing.
- Collecting information to support production of a viability matrix and value assessment.

At a high level, the thermal technologies were first classified into three ***process categories*** according to the type of product produced as follows:

- Thermal processes that are expected to generate a product that requires additional conditioning (e.g., encapsulation) to allow it to become suitable for disposal. These technologies can be described as treatment processes that are employed to reduce chemical reactivity and/or potentially reduce volume.
- Thermal processes involving immobilisation of radioactive waste by encapsulation in a glass matrix or by direct incorporation into the glass matrix.
- Thermal processes involving immobilisation of radioactive waste by incorporation in a ceramic matrix or in a glass/ceramic composite matrix.

For each process category above, a sub-level of classification was used to sort existing technologies by heating mode and process wall material (e.g. refractory or cold wall, etc.). For each technology, examples of existing facilities (commercial or laboratory scale) in Europe were then provided. The example facilities were only used to illustrate the possible variations that may exist within a treatment technology, and therefore are not exhaustive. Table 2 provides a summary of the classification that was adopted.

Table 2. Classification of thermal treatment and processing technologies considered in THERAMIN.

High-level process	Technology	Facility	Country
Treatment for volume reduction and passivation	Incineration with burner and refractory walls	JÜV 50/2 - Jülich JEN	Germany
		KTE incinerator	Germany
		EDF CENTRACO	France
	Rotary kiln incineration	IRIS	France
	Pyrolysis	Belgoprocess	Belgium
	Thermal gasification	VTT gasification	Finland
	Calcination	Widely used	France, UK
	Underwater plasma incineration	ELIPSE	France
	Hydrothermal Oxidation (HTO)	DELOS	France
	Induction metal melter	CARLA	Germany
		EDF CENTRACO	France
		Cyclife (formerly Studsvik)	Sweden
Conditioning by immobilisation in glass	Joule-Heated In-Can Vitrification	In-Can Melter and DEM & MELT (metallic inner wall), CEA	France
		GeoMelt (ceramic inner wall), NNL	UK
	Joule-Heated Ceramic Melter (JHCM)	VEK, PAMELA (both decommissioned)	Germany, Belgium
	Cold crucible induction melter (CCIM)	La Hague CCIM and Marcoule CCIM pilot	France
	Advanced CCIM (A-CCIM)	Marcoule A-CCIM pilot	France
	Indirect induction (metallic wall - hot metal pot)	VICHR	Slovakia
		La Hague and Sellafield	France, UK

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High-level process	Technology	Facility	Country
	Coupled cold wall direct metal induction melting and plasma burner	PIVIC	France
	Coupled cold wall direct glass induction melting and plasma burner	SHIVA	France
	Refractory wall plasma burning and melting	Retech (ZWILAG)	Switzerland
		EUROPLASMA – Belgoprocess	Bulgaria
		Tetronics	UK
Conditioning by immobilisation in ceramic or glass-ceramic	HIP	NNL – Workington and University of Sheffield	UK

A process summary table was generated for each technology in order to provide information to support Tasks 2.4 (viability matrix) and 2.5 (value assessment). For each of the European facilities included in the technology survey, information was provided by THERAMIN partners on the following topics:

- Waste compatibility with technology (solid, liquid, organic, inorganic, metal, level of activity, etc.).
- Mode of heating.
- Containment.
- Nature of product.
- Limitations of technology.
- Maximum volumetric throughput.
- Continuous or batch process.
- Secondary waste generation.
- Maturity of technology (TRL).
- Target date for active commissioning of full-scale industrial facility.
- Technological complexity.
- Flexibility to treat a wide range of waste types.
- For specific facilities, the size of furnace or crucible (or volume of waste that can be treated in one batch).
- Scaleability.
- Investment and operational costs.

The information collected under Task 2.1 (wastes) and Task 2.3 (technologies) was then used to derive a viability matrix in which the suitability of particular technologies to treat particular waste types was shown. The waste types were organised in the same way as in the THERAMIN waste database so that they could be linked directly to specific countries and, if needed, to specific waste streams.

For each waste type – technology combination, the key factors determining whether the combination is viable or not were considered. It was proposed that viability should be considered in two distinct ways:

- Wastes that can be processed in principle by a particular technology.
- Wastes that have been demonstrably processed by a particular technology.

To assess the potential to apply each of the thermal treatment technologies to the identified waste groups, it was essential to review some of their key properties. The D2.3 report [3] focuses on a number of specific attributes. Firstly, the types of waste that could be treated by each technology were assessed. This focused specifically on whether the technologies can treat solids, liquids, or both solids and liquids. It also considered whether they could treat organic or metallic wastes. In addition, the maximum accepted levels of activity which each facility can accept were highlighted. Finally, the flexibility of each technology was also determined to assess whether it could be used to treat a wide range of wastes, and/or highly heterogeneous waste streams.

To determine accurately the viability of each treatment technology, it is important not just to assess their beneficial attributes, but also the potential limitations that may render treatment challenging or impossible. The technical limitations inherent in each technology were therefore also considered (e.g., some technologies might be challenged by significant metal fraction in the waste feed). Additionally, each of the facilities are bound by logistical constraints including their maximum treatment capacity and throughput, and whether they have been made to operate at an industrial scale. These aspects were also considered as they are likely to inform decision making (e.g., a low capacity method may not be ideal for treating large waste volumes). Finally, the TRL of the technique was considered as some technologies, although theoretically able to treat a waste with the identified properties, may still only be at the experimental or pilot stage.

Considering all of the above information, the D2.3 report [3] presented a viability matrix linking the generic waste groups to the thermal treatment technologies. Each technology was categorised as either having already been tested to treat that waste, potentially having applicability, having only limited applicability, or not being applicable. A number of the technologies have been tested in THERAMIN WP3 on a range of wastes (Table 3).

Table 3. Waste-technology combinations tested in THERAMIN WP3 (cells highlighted and ticked).

Technology	**Sludge**	**Cement conditioned wastes**	**Organic ion-exchange material**	**Inorganic ion-exchange material**	**Ash**	**Inorganic liquor**
GeoMelt	✓	✓				
Hot Isostatic Pressing	✓			✓		
SHIVA			✓	✓		
In-can melter					✓	
VICHR Vitrification						✓
Thermal Gasification			✓			

4. Gap Analysis

The viability matrix and the THERAMIN waste database were used to facilitate a strategic gap analysis to identify countries where there are significant waste arisings with potential to benefit from thermal treatment using technologies available within the country or in other European countries. Where gaps in domestic technologies and facilities were identified, suggestions were made of resources available to process the wastes in other countries.

It is noted that the gap analysis is based on the viability matrix, where the treatment technology applicability to specific generic waste types takes into account the properties of the wastes and the technical aspects of the treatment technology. It does not account for non-technical constraints and limitations on waste treatment such as constraints on moving wastes across international borders for treatment, regulatory barriers, or stakeholder implications. In addition, the mapping does not consider detailed characterisation data and specific properties of the waste streams within a generic waste group. Therefore, the information in the strategic analysis provides only a preliminary input and a starting point to aid decision making, rather than a definitive or optimised options appraisal for treating a particular waste stream.

The analysis concluded that although a few European countries may have the resources to thermally treat their own wastes, many other countries could benefit from cross-country collaboration and treatment of wastes outside their borders. This could provide a cost-effective option to treatment of challenging and problematic wastes. Further information and country-by-country analysis are provided in the D2.3 report [3].

5. Conclusions

This paper presents the outcomes of an international review of inventory information concerning European wastes potentially suitable for thermal treatment, a review of thermal treatment technologies available in Europe, and a strategic gap analysis to identify countries where there are significant waste arisings with potential benefits for thermal treatment, but little prospect of these countries developing thermal treatment facilities independently.

The waste streams identified by project partners were categorised into 14 different generic waste groups and included in an electronic database. The survey of European thermal treatment technologies identified a wide range of techniques that could be grouped into three high-level process types: thermal treatment for volume reduction and passivation (eight technologies), conditioning by immobilisation in glass (eight technologies), and conditioning by immobilisation in ceramic or glass-ceramic matrices (one technology). Both the inventory database and the thermal technology survey outcomes allowed the creation of a viability matrix which maps the generic waste groups to thermal treatment technologies that could potentially treat the identified wastes. All these tools (i.e., the waste database, technology survey, and viability matrix) can be used by THERAMIN project organisations to aid in their decision making regarding potential suitable thermal technologies for their wastes.

Finally, a strategic gap analysis was undertaken to identify those countries with wastes identified as suitable for thermal treatment but with no suitable domestic thermal treatment facility. Facilities with the technological capability to treat those wastes in other European countries were identified. Although this analysis does not account for non-technical limitations on movement of waste across international borders, it provides preliminary inputs for future decision making and further analysis taking into account wider considerations on specific waste characteristics and other facility constraints.

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