Development of Generic Criteria for Evaluating the Disposability of Thermally Treated Wastes

Liz Harvey, Daniel Galson, Marie-Ange Romero, Stéphane Catherin, Maxime Fournier, Adam Fuller, Stephen Wickham

IOP Conf. Series: Materials Science and Engineering **818** (2020) 012013 doi:10.1088/1757-899X/818/1/012013

Development of Generic Criteria for Evaluating the Disposability of Thermally Treated Wastes

L Harvey[1], D Galson[1], S Catherin[2], M-A Romero[3], M Fournier[4], A Fuller[1], S Wickham[1]

[1]Galson Sciences Ltd, 5 Grosvenor House, Melton Road, Oakham, LE15 6AX, United Kingdom
[2]Cyclife – EDF Group, 20 Place de la Défense, 92050 Paris La Défense, France (formerly at ANDRA)
[3]ANDRA 1/7 Rue Jean-Monnet, 92298 Châtenay-Malabry, Paris, France
[4]CEA, DEN, DE2D, Univ. Montpellier, Marcoule, France

E-mail: ejh@galson-sciences.co.uk

Abstract. The potential to generate wasteforms with enhanced properties that support safe storage and disposal is one of the key factors driving thermal treatment of radioactive waste. Depending on the specific treatment method and waste substrate, thermal treatment can greatly reduce chemical reactivity, yielding a primary product that is more durable than wasteforms produced via non-thermal routes and with reduced potential for gas generation and other detrimental behaviour in a storage / disposal environment. On the other hand, thermal treatment can concentrate radioactivity into a smaller volume, potentially affecting waste handling and / or classification. It also generates secondary wastes whose management requires consideration as part of a holistic evaluation of thermal treatment. Moreover, some thermal treatment routes do not generate a primary product that is directly disposable without further conditioning.

Generic disposability criteria have been derived that can be used to evaluate the primary products from any form of thermal treatment. These generic disposability criteria highlight the factors that are relevant for waste product disposability and the ways in which thermal treatment can impact on these factors (both positively and negatively). They are equally applicable to any packaging or disposal concept, regardless of the engineered barriers that are present, and in any disposal environment, regardless of its characteristics and the nature of the host rock / geology. They could aid waste management organisations in developing their own disposability criteria, tailored to a particular context, for application in national waste management programmes.

1. Introduction

In order to be disposed of, radioactive wastes must comply with the Waste Acceptance Criteria (WAC) for a disposal facility. WAC identify the characteristics required in a waste product in order to ensure that the waste cannot have a significant detrimental impact on the long-term safety provided by the disposal facility. Compliance with WAC is confirmed by characterisation of the conditioned waste.
Work package 4 (WP4) of the European Commission (EC) THERAMIN project evaluated the disposability of thermally treated waste products and the resulting secondary wastes, considering

IOP Conf. Series: Materials Science and Engineering **818** (2020) 012013 doi:10.1088/1757-899X/818/1/012013

different waste stream / thermal treatment process combinations and the differing disposal concepts and national contexts of countries participating in THERAMIN. It was divided into three tasks [1]:

- *Task 4.1:* Identification and review of criteria and requirements for the disposability of thermally treated waste products. This task considered the relevance of existing WAC, and other requirements relating to the behaviour and performance of waste products, to thermal treatment. Approaches to characterise waste products to determine whether WAC / requirements are met were also defined. The work is reported in THERAMIN Deliverable D4.1 [2].
- *Task 4.2:* Characterisation of thermally treated waste products and secondary waste. Here, characterisation tests have been conducted on thermally treated waste products. Pre-existing data have also been shared. The results are reported in THERAMIN Deliverable D4.2 [3].
- *Task 4.3:* Downstream / Safety Case implications. This task considered the disposability of thermally treated waste based on the outputs from the two previous tasks. Associated deliverables will be published later in 2020.

This paper presents a set of generic disposability criteria that have been derived for thermally treated wastes under THERAMIN Task 4.1 and discusses considerations applicable when measuring compliance with these criteria. It also describes their application in THERAMIN to design a set of characterisation tests for the products from thermal treatment demonstrations, and to feed consideration of disposability into a wider 'value assessment' options evaluation methodology for different thermal treatment routes. The relevance of these disposability criteria for other ongoing EC projects, such as the EURAD ROUTES work package, is also outlined.

2. Generic disposability criteria developed under the THERAMIN project

2.1 Approach to derive generic disposability criteria

The disposability of thermally treated waste products and management of the resulting secondary wastes was examined by reviewing national WAC and other disposability requirements applicable in individual countries (collectively referred to here as 'national disposability criteria') and using these to derive a set of generic disposability criteria that can be applied more generally. Inputs were received from eight countries: Belgium, Finland, France, Germany, Lithuania, Slovakia, Switzerland and the United Kingdom. For each country, a short summary was prepared, setting out factors relevant to the management of radioactive waste and application of thermal treatment in that country, such as the approach to classify radioactive waste, a summary of the inventory, the status of disposal facilities, planned development activities and known issues. Existing criteria applicable to the disposability of thermally treated waste products were then compiled for each participating country. Table 1 summarises the scope of national disposability criteria inputs [2, §4.2].

Table 1. Summary of the scope of national disposability criteria inputs.

Country	Scope of inputs	Type of disposal	Packaging concept	Formal WAC?
Belgium	Planned disposal of short-lived low- and intermediate level waste (LILW) near Dessel in north-east Belgium	Surface	Storage packages grouted in concrete monoliths	No – preliminary – formal WAC will be finalised once a licence for disposal is obtained
Finland	LILW (reactor operating waste) disposal	Near-surface (Olkiluoto VLJ); intermediate-depth (Loviisa VLJ)	Concrete boxes	Yes
France	Long-lived intermediate-level waste (ILW) disposal in clay	Geological (in a clay host rock)	Storage packages grouted in concrete boxes / direct disposal	No – preliminary WAC submitted to the French Safety Authority in 2016

IOP Conf. Series: Materials Science and Engineering **818** (2020) 012013 doi:10.1088/1757-899X/818/1/012013

Country	Scope of inputs	Type of disposal	Packaging concept	Formal WAC?
Germany	Long-lived LILW disposal at Konrad in northern Germany	Geological (host rock to be determined)	Cast iron / steel / concrete boxes	Yes
Lithuania	Planned disposal of long-lived ILW	Geological (host rock to be determined)	Cement-grouted metallic waste	No – preliminary WAC
Slovakia	Low-level waste (LLW) disposal at Mochovce	Surface	Fibre-reinforced concrete packages	Yes
Switzerland	Planned disposal in clay (all radioactive waste)	Geological (clay)	Steel canisters / storage drums in concrete boxes	No – preliminary WAC
United Kingdom	Planned disposal of ILW (also applies to high-level waste/spent fuel disposal)	Geological (salt / clay / crystalline – host rock to be determined)	Waste grouted in steel / cast iron / concrete containers	Not WAC, but formal requirements – specifications to be met for issue of a Letter of Compliance (LoC)

2.2 Observations on national disposability criteria

It is important to note that existing national disposability criteria are not specific to the disposal of thermally treated wastes; they tend to be more generally applicable to all wastes of a certain classification or destined for a particular disposal route. This reflects the relative novelty of thermal treatment as a management route, particularly for LLW and ILW, compared to more conventional waste conditioning approaches such as cement encapsulation, and underpins the need for explicit consideration of criteria for thermally treated wastes. Also, the national inputs provided do not reflect all applicable WAC for radioactive waste disposal in the participating countries. Generally, those provided reflect the wastes that are currently being considered for thermal treatment.

There are some important distinctions between the national inputs received:

- National disposability criteria have been provided for various types of disposal facility, including surface disposal (in the case of responses from Belgium and Slovakia), near-surface disposal (Finland) and geological disposal (France, Germany, Lithuania, Switzerland, United Kingdom). Some criteria will vary depending on the depth of disposal and the safety functions applicable to the wasteform in different disposal contexts.
- For the most part, the national disposability criteria focus on the disposability of long-lived LLW and ILW, although some countries have provided inputs relating to the management of short-lived wastes (Belgium) or inputs that apply to both LLW/ILW and high-level waste (HLW)/spent fuel disposal (Switzerland, United Kingdom). The packaging approach(es) applicable to the different waste types (and reflected in national disposability criteria) depend on the disposal concepts that have been adopted for the relevant disposal facilities in each country, but generally involve disposal in concrete, steel or cast-iron containers.
- Some national disposability criteria have been provided that refer to generic plans for disposal (particularly in the cases of geological disposal in countries that have not yet identified a proposed site or host rock in which to construct a repository). In such cases, the criteria provided are preliminary / provisional, and will be developed further as plans for the disposal facility progress. Other national disposability criteria are site-specific and reflect formal WAC associated with an existing disposal facility (or one that is in the advanced stages of planning).

2.3 Suite of generic disposability criteria

Generic disposability criteria have been derived that can be used to evaluate the products from any form of thermal treatment. These generic disposability criteria highlight factors that are relevant for waste product disposability and the ways in which thermal treatment can impact on these factors (both positively and negatively). They have been developed to be applicable to any packaging or disposal

IOP Conf. Series: Materials Science and Engineering **818** (2020) 012013 doi:10.1088/1757-899X/818/1/012013

concept, for any thermally treated waste, regardless of the engineered barriers that are present, and in any disposal environment, regardless of its characteristics and the nature of the host rock / geology. They are intended to provide a starting point or point of reference for WMOs to tailor their own national disposability criteria to thermally treated waste in a manner that gives confidence that relevant factors are being considered.

The generic disposability criteria have been defined at a relatively high level, focusing on additional requirements and/or clarifications relating specifically to thermal treatment that can build on more widely applicable disposability criteria defined within national programmes. Qualitative, rather than quantitative, metrics are set out, against which disposability can be assessed. This is because numerical requirements identified within national disposability criteria tend to be strongly linked to the national context (e.g. activity limits for different waste classifications), so have limited transferability for wider use outside the country of origin.

Generic disposability criteria and associated considerations are set out in Table 2, based on WAC affected by thermal treatment. Further detail on the underpinning rationale for these criteria is provided in THERAMIN Deliverable D4.1 [2]. If used, these criteria and considerations would need to be applied in conjunction with existing criteria applicable to other wastes that are planned for disposal in a particular facility. They do not stand alone as a complete set of requirements that could underpin WAC for thermally treated waste.

Table 2. Generic disposability criteria specific to thermally treated waste products.

Topic / Category	Generic disposability criterion	Considerations applicable to measure compliance
Dimensions / mass of packages	The dimensions and mass of containers used to package thermally treated waste (and other aspects of the container design) should be compatible with (i) the thermal processing route being employed and (ii) relevant safety functions for storage and disposal, and with all applicable constraints on waste classification, handling, transport and disposal, taking account of the processed waste characteristics.	None.
Package integrity and required lifetime	Apply existing criteria for the disposal context in question. Any additional criteria on package integrity defined for thermally treated waste should be linked to safety functions applied to such waste.	The characteristics of thermally treated waste should be considered as part of demonstrating compliance with existing requirements.
Thermal output	The thermal output of thermally treated waste should not have a detrimental impact on performance of the engineered and natural barriers that make up the disposal system, taking account of the potential for activity to be concentrated during thermal treatment.	None.
Voids	Void space within packages of thermally treated waste should be minimised wherever practicable; this may influence aspects of how thermal treatment is implemented.	None.
Chemical content	Apply existing criteria for the disposal context in question. The choice of thermal treatment route and the design of the associated disposal facility should ensure the chemical compatibility of thermally treated waste with other disposal system components.	None.

Topic / Category	Generic disposability criterion	Considerations applicable to measure compliance
Chemical durability	Existing requirements on chemical durability for the applicable disposal route should be applied to thermally treated waste. No additional generic disposability criteria for thermally treated waste are considered necessary, although requirements relating to the containment provided by a wasteform may be justified, depending on the post-closure safety case.	If criteria relating to the durability of a thermally treated wasteform are deemed to be required for application in a particular context, then it is recommended that these should be linked to a required containment lifetime (as assumed in the relevant post-closure safety case), rather than to a threshold dissolution rate.
Data management	Data management requirements for the relevant disposal route should be applied to thermally treated waste. In addition, records of the thermal treatment regime applied to the waste should be kept.	None.
Secondary waste	Secondary waste associated with thermal treatment should be minimised to the extent that is practicable.	None.

In a number of other areas against which information on national disposability criteria was gathered, no additional disposability criteria relating specifically to thermally treated wastes are required beyond those already specified for wastes conditioned via non-thermal routes. Moreover, products from thermal treatment may be better able to meet certain existing WAC / requirements as a result of the processes taking place during the thermal treatment step. This is the case for requirements relating to:

- No free liquid/water or gas being present in the waste, since volatile species in the raw waste tend to be driven off.
- No hazardous material being present (and requirements for the waste product to be inert), since reactive waste constituents are typically consumed / destroyed during thermal treatment.
- Minimal gas generation from the waste product, again because of the destruction of reactive waste constituents.
- Production of a robust wasteform, noting that many waste constituents are oxidised / combusted during thermal treatment, ending up in an unreactive form, and the product of thermal treatment is often (although not always) monolithic, with waste species encapsulated or incorporated within a vitreous or ceramic waste matrix.
- Production of a homogeneous wasteform with no localised accumulations of radioactivity.
- Provisions associated with managing the potential for nuclear criticality.
- The wasteform exhibiting mechanical resistance to stresses likely to be imposed during transport, handling and disposal operations.
- Provisions for waste package transport, handling and emplacement, including waste package stacking.
- The waste package activity content.
- The waste package radionuclide inventory, noting that the choice and design of a thermal processing route should be tailored to the radionuclide inventory (and other characteristics) of the raw waste, particularly if thermal treatment is driven by a desire to produce a durable, long-lived wasteform.
- Waste package dose rate limits.
- Surface contamination of the waste package.
- Waste package accident performance, noting that susceptibility to high temperature excursions in the event of a fire is likely to be much reduced, given that the waste has already been subjected to high-temperature treatment.
- Waste package identification / labelling.
- Quality assurance / quality control arrangements.

IOP Conf. Series: Materials Science and Engineering **818** (2020) 012013 doi:10.1088/1757-899X/818/1/012013

However, additional considerations relating to the impacts of thermal treatment and the characteristics of the resulting product are often relevant when determining whether existing, more generally applicable criteria have been met. Such considerations include:

- The potential for thermal treatment to concentrate radioactivity and fissile material in the waste product (and thereby to increase heat generation per unit volume).
- The impacts of generating a relatively high density, low voidage wasteform in many cases, which could affect waste package handling.
- The potential for thermal treatment to introduce new mechanisms for contamination of equipment and/or waste packages (e.g. splashing, particulate generation and/or carry-over to the off-gas system).
- The chemistry and mechanical properties of thermally treated wastes, which may behave differently during handling, storage and disposal, thereby introducing new uncertainties relating, for example, to chemical compatibility in a disposal environment.
- Safety functions applicable to thermally treated wastes may or may not be the same as those applicable to other wastes to be disposed of in the same facility, depending on the drivers for implementing thermal treatment. Evaluation of thermally treated waste in the post-closure safety case for a disposal facility may therefore differ from that for other wasteforms.

3. Design of characterisation tests for products of thermal treatment

Having collated national disposability criteria and derived generic disposability criteria, an exercise was conducted to identify WAC requiring characterisation of thermally treated waste products in order to test compliance, along with identification of suitable analytical techniques to meet these characterisation requirements. Table 3 summarises criteria identified as requiring characterisation tests to be performed, and identifies physico-chemical properties that can be measured to evaluate whether each of these criteria have been met, along with some examples of applicable, commonly used, measurement techniques. It can be seen that most criteria can be verified through the use of electron microscopy, possibly combined with analyses of the chemical and radiological composition of the sample. However, some WAC require more specialist techniques to measure compliance.

Table 3. Measurable properties and techniques applicable for verifying whether WAC have been met.

Waste Acceptance Criterion	Properties	Examples of Applicable Techniques
No, or limited, free liquid or gas and limited potential for gas generation	Homogeneity of the waste	Thermogravimetric analysis (TGA), X-ray fluorescence (XRF), electron microscopy
Permeability and/or diffusivity of the waste sufficient to enable gas to escape without affecting wasteform integrity	Permeability + diffusivity	XRF, electron microscopy
No or limited content of hazardous materials (combustible, pyrophoric, reactive, etc.)	Homogeneity of the waste (no untreated area) + identification of chemical species in the waste	XRF, X-ray diffraction (XRD), Inductively coupled plasma (ICP) analysis after dissolution
Immobilisation of radionuclides, including homogeneity and passive safety under both normal and ‘accident’ conditions.	Distribution of radionuclides in the waste	α-spectrometry, autoradiography, Raman spectroscopy
Limited voids / limited porosity (e.g. to limit the potential for collapse of waste package stacks in a disposal facility)	Porosity	Wide-angle X-ray scattering (WAXS), surface area measurement by gas physisorption, porosimetry
No localised accumulations of radioactive material	Homogeneity of the waste / microstructure	XRF, electron microscopy

Waste Acceptance Criterion	Properties	Examples of Applicable Techniques
Chemical durability of the waste product	Chemical durability (leaching behaviour)	Leaching tests, ICP, ion chromatography, UV-Visible spectroscopy, α-spectrometry
Mechanical resistance of the waste product to stresses imposed during transport, handling and disposal operations	Mechanical behaviour	Mechanical resistance test methods (compression, tension,)
Limited or no metal, e.g. in Belgium: no metal with a redox lower than 0.84 V Standard Hydrogen Electrode (SHE) (specified because of the potential for such metals to corrode and produce significant quantities of hydrogen gas).	Homogeneity of the waste / microstructure	XRF, electron microscopy, optical microscopy
Thermal conductivity of the waste product (especially for self-heating waste)	Thermal conductivity / thermal behaviour	Thermal conductivity measurement

This exercise was used as the basis for planning characterisation tests conducted under THERAMIN Task 4.2. The results of these tests are reported in THERAMIN Deliverable D4.2 [3] and are the subject of several other papers published elsewhere in this issue of *IOP Conf. Ser.: Mater. Sci. Eng*.

Such tests would only need to be conducted on selected products from an industrial-scale thermal treatment facility, assuming that quality controls guarantee the representativeness and transferability of tests conducted on sample materials.

4. Disposability inputs to THERAMIN value assessment

A value assessment approach has been developed under THERAMIN WP2. It provides a structured methodology for evaluating the potential application of a thermal treatment technology to treat a waste stream of interest. 'Value' in this context is defined as realisable benefit in safety, monetary and/or environmental outcomes from implementing an option at a specified time. This includes benefits and challenges across all stages of the waste management lifecycle. The value assessment methodology aims to integrate learning from across the THERAMIN project.

The methodology developed employs a multi-attribute assessment approach that builds on the UK Nuclear Decommissioning Authority's (NDA's) value framework [4]. The following assessment attributes are included in the THERAMIN value assessment methodology:

- Operational and transport safety
- Environment impact
- Impact on disposability and long-term safety
- Factors affecting the implementation of a thermal treatment technology
- Timescales
- Technical readiness of the technology
- Strategic cost impacts

Each of these attributes is sub-divided into a series of 'data categories', accompanied by a set of assessment considerations that provide guidance to the user on factors to consider when conducting a value assessment. Two data categories are defined under the impact of disposability and long-term safety attribute: the ability to meet applicable WAC and the disposability of secondary waste. The generic disposability criteria described in this paper are the principal suite of assessment considerations relating to these data categories, alongside identification of potential disposal routes for secondary waste. Further information on the THERAMIN value assessment methodology is provided in [5].

5. Links to other EC projects

Several other collaborative EC projects are considering, or have recently considered, the development and application of WAC within their work programmes, albeit with differing areas of interest and emphasis (and not focused on thermal treatment as in THERAMIN). There are opportunities for synergy across projects and a need to ensure future project activities learn from recent developments.

The EC Horizon 2020 project **"CHANCE"** (Characterization of Nuclear Waste for its Safe Disposal in Europe) aims to address issues associated with the characterisation of conditioned wastes. It aims to establish, at the European level, a comprehensive understanding of current conditioned radioactive waste characterisation and quality control schemes across national radioactive waste management programmes, and to further develop, test and validate techniques that will improve the characterisation of conditioned radioactive waste, particularly those that cannot easily be studied using conventional methods. Knowledge of applicable WAC is an important input to CHANCE in order to identify characterisation requirements, and was a focus area for a recent information gathering exercise [6].

WAC are also considered within WP9 **("ROUTES")** of the European Joint Research Programme on Radioactive Waste Management (EURAD), which commenced in June 2019 and runs for five years. ROUTES focuses on waste management routes in Europe from cradle to grave. It aims to:

- Provide an opportunity to share experience and knowledge.
- Identify safety-relevant issues and their research and development needs.
- Compare characterisation, treatment, conditioning and long-term waste management strategies, and identify opportunities for collaboration between European Union (EU) Member-States.

Task 4 of ROUTES involves identification of WAC used in Member-States for different disposal alternatives in order to inform development of WAC in countries without WAC / disposal facilities. Countries will also share experience of managing challenging wastes without a final disposal solution.

Both WAC and thermal treatment will be considered under the auspices of a new (still to be approved) EC project **"PREDIS"** (Pre-disposal Management of Radioactive Waste), which is expected to run for four years from June 2020. The objectives of PREDIS include developing new solutions for treatment and conditioning of waste for which no industrially mature or adequate solution is currently available, and improving existing solutions with safer, cheaper or more effective processes. Work packages will focus on metallic, liquid organic, solid organic and cemented wastes, as well as considering wider strategic implementation of treatment and conditioning solutions. The wider investigation of generic WAC also forms part of PREDIS.

Acknowledgements
This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 755480. This paper reflects the authors' views and the European Commission is not responsible for any use that may be made of it.

References

[1] Scourfield S J, Kent J E, Wickham S M, Nieminen M, Clarke S, Frasca B 2020 Thermal treatment for radioactive waste minimisation and hazard reduction: overview and summary of the EC THERAMIN project, *IOP Conf. Ser.: Mater. Sci. Eng* same issue
[2] Andra *et al.* 2018 *Waste Acceptance Criteria and requirements in terms of characterisation*, European Commission THERAMIN Deliverable D4.1.
[3] Andra *et al.* 2019 *Characterization of thermally treated waste products*, European Commission THERAMIN Deliverable D4.2.
[4] Nuclear Decommissioning Authority 2016 *The NDA Value Framework*, Version 1.2.
[5] Fuller A, Doudou S, Kent J, Harvey L, Wickham S 2020 *Assessing the value of thermal treatment technologies, IOP Conf. Ser.: Mater. Sci. Eng* same issue.
[6] Bucur C, Dodaro A, Ferruci B, Meskens G, Ricard D, Tietze-Jaensch H, Thomas P and Turcanu C 2019 *Synthesis of commonly used methodology for conditioned radioactive waste characterization*, European Commission CHANCE Deliverable D2.2.